Universidade de Aveiro
2008

Departamento de Electrónica, Telecomunicações e Informática

Sérgio Miguel Calafate de Figueiredo

Avaliação de ferramentas de simulação e modelação de redes

Evaluation of network simulation and modeling tools

Universidade de Aveiro
2008

Departamento de Electrónica,
Telecomunicações e Informática

Sérgio Miguel Calafate de Figueiredo

Avaliação de ferramentas de simulação e modelação de redes

Evaluation of network simulation and modeling tools

dissertação apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Mestre em Engenharia Electrónica e Telecomunicações, realizada sob a orientação científica do Dr. António Nogueira, Professor Auxiliar, e do Dr. Paulo Salvador, Professor Auxiliar convidado, ambos do Departamento de Electrónica, Telecomunicações e Informática da Universidade de Aveiro.

Dedico este trabalho à minha familia, em especial aos meus pais, pelo apoio contínuo que me deram a todos os níveis, e ao meu irmão, por todo o conhecimento que me transmitiu durante a minha formação académica.

o júri

Presidente

Doutor Armando José Formoso de Pinho
professor associado da Universidade de Aveiro

Doutor Joel José Puga Coelho Rodrigues
Professor Auxiliar do Departamento de Informática da Faculdade de Ciências da Engenharia da Universidade da Beira Interior

Doutor António Manuel Duarte Nogueira (Orientador)
Professor Auxiliar da Universidade de Aveiro

Doutor Paulo Jorge Salvador Serra Ferreira
Professor Auxiliar Convidado da Universidade de Aveiro (Co-Orientador)

agradecimentos

I want to thank my supervisor and co-supervisor, António Nogueira and Paulo Salvador, respectively, for supporting my decision to embrace this project. I am indebted to them for their valuable proposals regarding the development of this thesis.

I would also like to thank the Institute of Telecommunications – Aveiro University pole, for the whole support.

I will not forget to express my gratitude to my friends, met through my academic journey, either in Portugal or in Czech Republic during my Erasmus experience. All the experiences shared with them certainly helped me to get where I am today, so it's fair to dedicate a portion of this work to them.

A very special bow of my gratitude goes to my family, in particular my parents and brother, who motivated and supported me from the beginning to the end; I hope one day I will be able to pay such debt.

.

palavras-chave Simulação de redes, modelação de tráfego, modelação de redes, previsão de qualidade de serviço / desempenho

Resumo

A crescente globalização da Internet e consequente procura de largura de banda nas redes *IP* existentes fez emergir a necessidade de um melhor planeamento das redes de telecomunicações. Tendo em vista esse fim foram criadas ferramentas aptas a auxiliar a gestão de redes, como software de monitorização, e em particular os simuladores de redes. Estes permitem a obtenção de resultados preciosos sem a consumo de recursos que a criação de uma testbed real requer. Um desses simuladores é o Opnet Modeler, um software comercial que possibilita a configuração de cenários a vários níveis, como as características dos protocolos, perfis de utilizadores e de mobilidade, ou a estrutura e dimensão da rede.

Esta dissertação propõe-se a numa primeira parte a analisar vários aspectos respeitantes à utilização do Opnet Modeler no prisma do gestor de redes, em especial em redes à escala de Campus, explorando algumas das vantagens e lacunas na sua utilização para diversos fins, tais como o design ou restruturação de redes e a análise da qualidade de serviço de diferentes aplicações.

Uma componente indispensável à gestão de redes é a previsão de qualidade de serviço. O facto do comportamento do tráfego numa rede variar devido a factores como a alteração do número de utilizadores ou dos seus perfis de tráfego, leva a que seja várias vezes necessário estimar o comportamento da rede sem o perfeito conhecimento desta ou dos seus recursos. O nível de tráfego actualmente desperdiçado devido a uma incorrecta estimativa por parte dos ISP's da utilização de redes mais complexas representa ao mesmo tempo custos desnecessários e recursos subaproveitados. A procura de um modelo de tráfego que possibilite uma aproximação mais exacta dos parâmetros previstos em relação à realidade leva a que haja uma maior investigação nesta área. Nesta dissertação é testado um *framework* modelador que se baseia apenas em medições (ou resultados de simulações) de tráfego e correspondentes parâmetros de qualidade de serviço dos pontos de acesso da rede, sem o conhecimento *a priori* da matriz de tráfego e da topologia da rede, para prever a qualidade de serviço em condições distintas.

Keywords

Network simulation, traffic modelation, network modelation, QoS / performance prediction

Abstract

The growing Internet globalization and consequent demand for bandwidth in the existing IP networks lead to the emerging need of a better network telecommunications planning. In order to accomplish that, apt network management tools were created, like monitoring software and network simulators, in particular. These allow the collection of precious results exempt of the resources consumption that the use of a real testbed would require. One of those simulators is Opnet Modeler, commercial software that allows to configure the scenarios at multiple levels, like protocol characteristics, profiles and mobility profiles, or the network size and structure.

This dissertation proposes to analyze various aspects related to Opnet Modeler use in a network manager perspective, in particular in Campus scale networks, aiming to explore its advantages and gaps when used for goals such as network design or restructuration and for different services' QoS analysis.

One essential component in network management is QoS prediction. The fact that the network traffic behavior varies due to details like the change in the number of users or their traffic profiles, many times leads to the need of assessing the network behavior without the perfect knowledge of the network or its resources. The currently wasted bandwidth by the ISP's and network managers due to an incorrect assessment of the utilization in more complex networks represents unnecessary costs and wasted resources. The pretension to obtain a traffic model that allows a more exact approximation of the predicted parameters relatively to the reality lead to a major increase in the research in this area. In this dissertation, the evluation of a modeling framework is performed; that model, based only in traffic measurements (or simulation results) and corresponding QoS parameters at the network access points, that is, without the a priori knowledge of the network's traffic matrix and topology, is able to predict the network's QoS for different conditions.

TABLE OF FIGURES V

TABLE OF GRAPHICS VII

TABLE OF ACRONYMS IX

1 INTRODUCTION 1

1.1 Objectives 2

1.2 Network Simulation Tools 3
1.2.1 OMNeT++ 4
1.2.2 Ns-2 4
1.2.3 Opnet Modeler 5
1.2.3.1 Opnet Network Modeling 6

1.3 Structure of the Dissertation 8

2 OPNET PROJECT IMPLEMENTATION 9

2.1 Introduction 9

2.2 Components 9

2.3 Simulated Network 12

2.4 Profiles and settings 14
2.4.1 Settings 15
2.4.2 User profiles 17
2.4.2.1 Profile 1 - Light Internet user 18
2.4.2.2 Profile 2 – Medium Internet user 19
2.4.2.3 Profile 3 - Multimedia Internet user 19
2.4.2.4 Profile 4 - Heavy Internet user 20
2.4.2.5 Profile 5 – Mobile Internet user 21
2.4.2.6 QoS Evaluation Profiles 22

2.5 Collected Statistics 24

2.6 Profiles results 25

2.7 Conclusion 26

3 SIMULATION SCENARIOS 27

3.1 Introduction **27**

3.2 Full Campus Simulations **27**
3.2.1 Ethernet LAN 27
3.2.1.1 Scenario 1 – Light internet user profile 28
3.2.1.2 Scenario 2 – Internet medium user profile 29
3.2.1.3 Scenario 3 – Internet multimedia user profile 29
3.2.1.4 Scenario 4 – Internet heavy user profile 30
3.2.2 Wireless Ethernet LAN 31
3.2.2.1 Scenario 5 – Wireless Network 32
3.2.2.2 Scenario 6 – Wireless Network with roaming 33
3.2.3 Campus simulation results 34

3.3 QoS Evaluation **36**
3.3.1 Case study 1 – High link utilization network 38
3.3.2 Case study 2 – Overflowed network 38
3.3.3 Case study 3 – Network with multiple user profiles 39
3.3.4 QoS evaluation results 40

3.4 Conclusion **42**

4 TRAFFIC MODEL IMPLEMENTATION **45**

4.1 Introduction **45**

4.2 Network model concept **45**

4.3 Application of the Model in a Campus Network **47**
4.3.1 Users Profile 48
4.3.2 Proposed scenarios 48
4.3.3 Results 50
4.3.4 Conclusion 52

5 FINAL REMARKS **53**

APPENDIX A – SUGGESTIONS FOR OPNET SCENARIOS BUILDING **55**

APPENDIX B – GRAPHICAL RESULTS **57**

B.1 Campus Scenarios **57**

B.2 QoS Scenarios **64**

B.3 Model Implementation..66

BIBLIOGRAPHY 69

TABLE OF FIGURES

FIGURE 1-1 - OMNET++ SIMULATION TOPOLOGY 4
FIGURE 1-2 - NS2 SIMULATION TOPOLOGY 5
FIGURE 1-3 – OPNET DIFFERENT CONFIGURATION LEVELS 6
FIGURE 2-1 – NODES LIST 11
FIGURE 2-2 - SCENARIO A 12
FIGURE 2-3 – SCENARIO B 13
FIGURE 2-4 - DEPARTMENT STRUCTURE ON OPNET (FOR 5 USERS) 14
FIGURE 2-5 – ANALOGY REGARDING OPNET PROFILES AND APPLICATION CONFIGURATION 15
FIGURE 2-6 - STRUCTURE USED FOR PROFILE ANALYSIS 18
FIGURE 3-1 - QOS EVALUATION SCENARIO ON OPNET 37
FIGURE 3-2 - DEPARTMENT STRUCTURE FOR CASE STUDY 1 38
FIGURE 3-3 - DEPARTMENT STRUCTURE FOR CASE STUDY 2 39
FIGURE 3-4 - DEPARTMENT STRUCTURE FOR CASE STUDY 3 40
FIGURE 4-1 – NETWORK MODEL CONCEPT 46
FIGURE 4-2 – STRUCTURE OF THE NETWORK USED FOR MODEL ANALYSIS 48

TABLE OF GRAPHICS

Graphic 2-1 - Profile 1 throughput (Kb/s) 18
Graphic 2-2 – Profile 1 throughput (packets/s) 18
Graphic 2-3 – Profile 2 throughput (Kb/s) 19
Graphic 2-4 – Profile 2 throughput (packets/s) 19
Graphic 2-5 – Profile 3 throughput (Kb/s) 20
Graphic 2-6 – Profile 3 throughput (packets/s) 20
Graphic 2-7 – Profile 4 throughput (Kb/s) 21
Graphic 2-8 – Profile 4 throughput (packets/s) 21
Graphic 2-9 – Profile 5 throughput (Kb/s) 22
Graphic 2-10 – Profile 5 throughput (packets/s) 22
Graphic 2-11 - User throughput for Profile A (Kb/s) 24
Graphic 2-12 - User throughput for Profile B (Kb/s) 24
Graphic 2-13 - User throughput for Profile C (Kb/s) 24
Graphic 2-14 – Profile 1 user round-trip time (µs) 26
Graphic 2-15 – Profile 2 user round-trip time (µs) 26
Graphic 2-16 – Profile 3 user round-trip time (µs) 26
Graphic 2-17 – Profile 4 user round-trip time (µs) 26
Graphic 2-18 - Profile 5 user round-trip time (µs) 26
Graphic 2-19 – Profiles A, B and C round-trip time (µs) 26
Graphic 3-1 – Scenario 1 throughput (kb/s) for unique scenario 28
Graphic 3-2 – Scenario 1 throughput (kb/s) using scenario division 28
Graphic 3-3 – Scenario 2 throughput (kb/s) 29
Graphic 3-4 – Scenario 3 throughput (kb/s) for 5 users 30
Graphic 3-5 – Scenario 3 throughput (kb/s) for 10 users 30
Graphic 3-6 – Scenario 4 throughput (kb/s) for 5 users 31
Graphic 3-7 – Scenario 4 throughput (kb/s) for 10 users 31
Graphic 3-8 – Scenario 5 throughput for 1 mobile user per department (kb/s) 33
Graphic 3-9 – Scenario 5 throughput for 3 mobile users per department(kb/s) 33
Graphic 3-10 – Scenario 6 throughput (kb/s) 34
Graphic 3-11 – Scenario 1 RTT (unique scenario) 35
Graphic 3-12 – Scenario 1 RTT (split scenario) 35
Graphic 3-13 – Scenario 2 RTT 35
Graphic 3-14 – Scenario 3 RTT 35
Graphic 3-15 – Scenario 4 RTT 35
Graphic 3-16 – Scenario 5 RTT 35
Graphic 3-17 – Scenario 6 RTT 36
Graphic 3-18 - Main link utilization for case study 1 38
Graphic 3-19 – Main link utilization for case study 2 39
Graphic 3-20 – Main link utilization for case study 3 40
Graphic 3-21 – Case study 1 end-to-end delay 41
Graphic 3-22 – Case study 2 call Jitter 41
Graphic 3-23 – Case study 2 end-to-end delay 41
Graphic 3-24 – Case study 2 call Jitter 41
Graphic 3-25 – Case study 3 end-to-end delay 42
Graphic 3-26 – Case study 3 call Jitter 42
Graphic 4-1 – CEMED department throughput 49

GRAPHIC 4-2 – RTT OBTAINED BY SIMULATION AND PREDICTED BY THE INFERRED NETWORK MODEL USING SIGMOID TRANSFORMATION 50
GRAPHIC 4-3 - RTT OBTAINED BY SIMULATION AND PREDICTED BY THE INFERRED NETWORK MODEL USING TAN-SIGMOID TRANSFORMATION 50
GRAPHIC 4-4 – RTT OBTAINED BY SIMULATION AND PREDICTED BY THE INFERRED NETWORK MODEL USING LINEAR TRANSFORMATION 50

TABLE OF ACRONYMS

AP → Access Point
BSS → Base Station Subsystem
CoS → Class of Service
CPU → Central Processing Unit
FCAPS → Fault, Configuration, Accounting, Performance and Security
FSM → Finite State Machine
FTP → File Transfer Protocol
GUI → Graphical User Interface
HDTV → High Definition Television
IP → Internet Protocol
IPTV → Internet Protocol Television
ISP → Internet Service Provider
ISO → International Organization for Standardization
IT → Information Technologies
ITU → International Telecommunication Union
ITU-T → ITU Telecommunication Standardization
LAN → Local Area Network
MANET → Mobile Ad-hoc Network
MPLS → Multi Protocol Label Switching
NMS-OSS → Network Management Systems and Operations Support Systems
OSI → Open Systems Interconnection
P2P → Peer to peer
PCM → Pulse Code Modulation
PDA → Personal Digital Assistant
PPP → Point to Point Protocol
QoS → Quality of Service
RTT → Round Trip Time
SLA → Service Level Agreement
TCP → Transport Control Protocol
ToS -→Type of Service
UDP -→User Datagram Protocol
VoIP → Voice over IP
WLAN → Wireless Local Area Network

1 Introduction

The understanding of network performance and effectiveness by nowadays network managers can only be described as crucial. The correct accomplishment of this task can be observed at different scales, whether in users' satisfaction or at a business success. Thus, a correct network planning, whether by ISP's or enterprises' IT teams affects end-users internet connectivity.

This correct planning is ensured by applications and technologies used in the Network Management and the NMS-OSS (Network Management Systems and Operations Support Systems) area, using different functions from the FCAPS (Fault, Configuration, Accounting, Performance and Security) ITU standard model.

Performance management refers to the data gathering and statistical data analysis for "*monitoring and correcting the behaviour and effectiveness of the network elements, or other equipment and to aid in planning, provisioning, maintenance and the measurement of quality*", by ITU-T definition (M.3400 and X.700, *Definitions of the OSI Network Management Responsibilities*). Therefore, performance management can be considered to deal with three distinct processes:

Performance monitoring — The collection of network activities at the device level regarding device-related, network and service performances monitoring. The sub processes used for this are: availability monitoring, response time reporting, utilization monitoring, accuracy assurance of the collected data, verification of QoS parameters, and data aggregation.

Data analysis— Baselining and reporting, done through network and device traffic characterization and analysis functions, performance, exceptions, capacity analysis, baselining and traffic forecasting.

Performance management — While monitoring only watches network activities, management modifies device configurations. Performance management represents the configurations adjustment to improve the network's performance and traffic handling (threshold definitions, capacity planning, etc). Again this main task is obtained through different sub processes: SLA's and CoS policies and guarantees assurance, threshold definition, notifications sending to higher level applications, configurations adjustment and QoS assurance.

This dissertation will in the first part focus in the network performance study for various scenarios, using a powerful network simulator, Opnet Modeler v12.1 (Note: In future references, Opnet Modeler will be referred simply as Opnet). In the following lines, the main goals will be revealed, and then some of the existing simulation tools will be listed and described.

1.1 *Objectives*

The work in this dissertation progressed having as main goal one idea- Opnet Modeler usefulness as a Campus network management tool. This idea implied the simulation of various testbeds in order to reach a more exact idea on how the simulation tool can be advantageous, and for what kind of tasks it is better suited. Therefore, with the experience acquired throughout the scenarios, a description of the program practical use facing different tasks will be shared.

The main study was done for Campus-sized scenarios, and the network behavior was observed for diverse conditions, as the inclusion of mobility, the variation in the users' behavior and number. The observed and evaluated metrics were those useful to a network manager, like link throughput, round-trip time, end-to-end delay or jitter, depending on the faced task.

It must be noted that it is not an objective to compare Opnet with other existing simulation networks, as it would also be extremely difficult, given the available time, to evaluate the different tools with the same degree of detail as was done for Opnet. Nevertheless, a brief overview of some simulation tools and their main functionalities and characteristics is presented. This dissertation pretends to help in deciding whether or not Opnet is an efficient and helpful network management tool, confronting advantages and disadvantages found out in the different situations for which it was used. This evaluation will include the major adversities noticed, the learning curve, and distinctive characteristics – that is, the user experience.

1.2 *Network Simulation Tools*

The creation of real testbeds for any specified scenario is an expensive or even impossible task, when considering factors like mobility, testing area, costs, time frame, etc. Another problem is the impossibility of repeating some measurements, or the increased requirements to do so. The basis for this dissertation is the networks' empirical analysis: that is, planning networks behavior based on simulation experiments. That's networks simulators biggest advantage. These are programs that model the behavior of a network either by calculating the interaction between the different network entities (hosts, data links, packets) using mathematical formulations, or actually capturing and playing back observations from a production network. The behavior of the network, the various applications and services it supports can then be observed in a controlled environment, and the various network's attributes can be modified in a controlled way to estimate how the network would behave under different conditions.

Existing simulation tools differ in accuracy, ease of use, speed, and monetary cost, and are often categorized by the simulation method used: discrete event or analytical simulation. In discrete event simulation, the system is represented by a sequence of events, where each event marks a state change in the system: the prediction is done at a low level (packet-by-packet), reason why it's slower but more accurate. Analytical simulation produces results using mathematical models, at a greater speed, but less accurately.

When simulating, one of the most demanding problems is deciding the detail level to implement, that can go from the devices selection to the used models and protocols. That single issue decides the usefulness of the simulation results, so there should be balance between the detail and computational cost, providing trusted results without consuming too much time.

Three of the most popular tools among academic and commercial communities are Opnet, Ns-2 and OMNeT++. Many studies can be found describing each of these tools, but little was written in terms of a network simulation tools comparison. As said by Bjorn Schilling; in "Opnet Modeler and Ns-2: Comparing the Accuracy of Network Simulators for Packet-Level Analysis using a Network Testbed", the reason for this is that most developers are familiar with only one of the simulators – for example, the tests done for this dissertation were done exclusively with Opnet. This turns out to be a problem when deciding which tool using for a specific purpose, as each one has its advantages and disadvantages, and there's not much useful background to help in this decision. That lack of knowledge leads to a decision to be taken based mainly on the available financial resources: whether ns2 and OMNeT++ more suitable for researchers and students, or Opnet for commercial and production environments. These three tools will now be shortly presented.

1.2.1 OMNeT++

OMNeT++ can be described as having an open-source, modular and component-based environment, along with GUI support and an embeddable simulation kernel. It's greatly used by the scientific community and also for industrial settings; the areas in which it is used range from communication networks simulation (mostly) to queuing networks, hardware architectures and even business processes. Advantages in its use are its flexibility and easy-access to published simulation models.

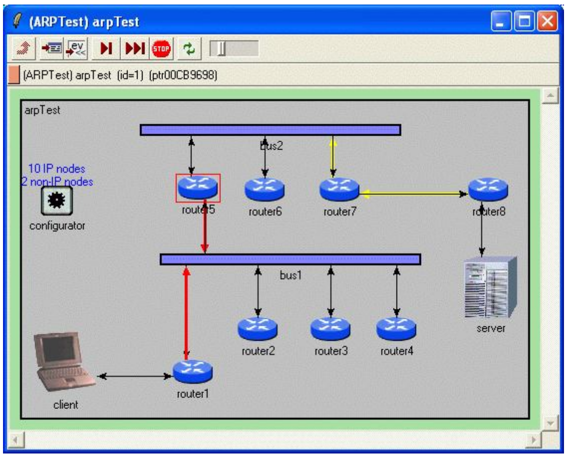


Figure 1-1 - OMNeT++ simulation topology

1.2.2 Ns-2

Ns-2 is an event-driven network simulator that includes various models of Internet protocols, as well as plenty online documentation. A network animator, Nam, provides packet-level animation and protocol specific graph for design and debugging of network protocols. Its open source nature is one of the key features, allowing different levels of configuration, like the possibility of creating custom applications and protocols, and also parameters configuration at different layers. This tool is commonly used in the simulation of routing and multicast protocols, but also for network research.

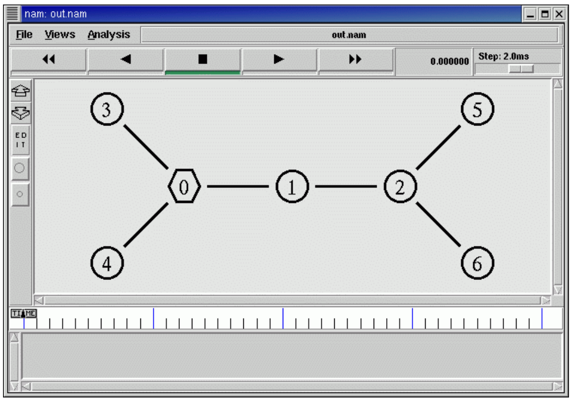


Figure 1-2 - Ns2 simulation topology

1.2.3 Opnet Modeler

Opnet is a very flexible and scalable application, which provides many customization features. The framework is based on object-oriented simulation approach supported by a series of graphic user interface-editors, which simplify the process of communication networks modeling, devices and protocols. The Project Editor enables the entry of graphic description of network topology. These editors represent the 3 main levels of the program:

The higher level is the Network Editor, which manages devices structures like LAN’s, WAN’s, etc. In this domain, subnets, network nodes and network links are treated as objects. The Node Level is used for describing protocols, and the connection between them, by using layers of the ISO/OSI model for communication devices. In this domain, the modules which represent the logic of the communication process occurring in each node are treated as objects. The Process Level uses a FSM approach to represent the different communication algorithms and protocols, like IP and TCP; the activity of individual state in FSM is implemented by programming in C language. Here, the states of each communication module are treated as objects.

The different levels are represented in figure **1-3**. Opnet incorporates a lot of pre-built simulation models of standard communication equipment and protocols for wired, radio and optical transmission mediums. The user interface offers several options and templates that let users drag and drop several kinds of network topologies. All these functionalities come at one cost, as Opnet is not open-source software – it's necessary to pay for a license. That also explains the use of a user-friendlier GUI, more characteristic of commercial software.

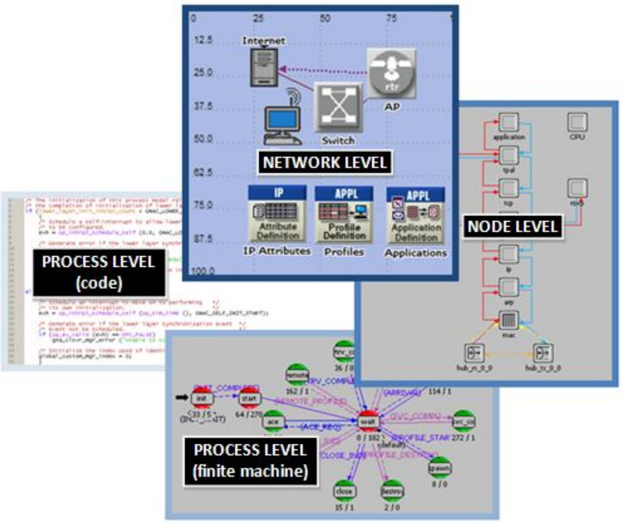


Figure 1-3 – Opnet different configuration levels

1.2.3.1 Opnet Network Modeling

The key to network modeling is the ability to closely match the generated network model map to the real network topology. Events such as link failure, link change, device failure, load change, route change and link overloading should be accurately modeled. Opnet generates all traffic using a junction between deterministic and stochastic modeling. A deterministic model is one in which every set of variable states is uniquely determined by parameters in the model and by sets of previous states of these variables. Therefore, deterministic models perform the same way for a given set of initial conditions. On the other hand, in a stochastic model, randomness is present, and variable states are not described by unique values, but rather by probability distributions. Opnet allows for two basic methods of network traffic modeling: explicit traffic and background traffic. In explicit traffic, also known as packet-by-packet traffic, Opnet produces every packet separately. In this manner, the traffic of the real system is clearly imitated; however such simulation is more demanding in terms of computational requirements. There are 3 methods for modeling explicit traffic:

→ Traffic generator: the modeling on the network node determines the exact size of the packets streams.

→ Application traffic model: traffic is generated by standard or customized application models.

→ Application demands: traffic is assigned between two nodes.

Background traffic is analytically modeled traffic, which has an influence on the properties of a system in the form of additional delay. It can also be used in combination with explicit traffic. There are also 3 methods for modeling background traffic on Opnet:

→ Traffic flow: describes finite end-to-end traffic from source node to destination node.

→ Baseline load: represents background traffic on one of the selected links (or from the node).

→ Application demands: can also be used to represent background traffic between two nodes.

The different explicit traffics will now be more extensively described:

Traffic generator: Opnet is able to model network traffic using a traffic generator, where the traffic is described statistically by packet size and time between packets (inter arrival time). There are approximately 20 different probability distributions available. Traffic generators in Opnet can be used for node models (stations) such as Ethernet IP station, PPP IP station and MANET station. In some models, like the WLAN station, beside these 2 parameters there is also the possibility of modeling the distribution of probability for active and non-active states of the node (ON state and OFF state).

Application traffic models: Opnet contains 16 standard-application traffic models that can be used on such node models as WLAN, MANET or Ethernet workstation. Examples of these are web browsing (light or heavy), FTP (light or heavy), voice application, etc, and a large amount of parameters can be changed for every model of application, such as: size of packets, amount of packets (data rate), transport protocol, number of times the sending is repeated, timeouts, retransmissions, failure and recovery, etc. In addition to using standard applications it’s also possible to model new custom application.

Application Demands: Application demands represent a way for modeling traffic where the applications' behavior is modeled. Demands characterize traffic by the sizes and rates of the requests and responses between two nodes in both directions.

1.3 *Structure of the Dissertation*

This dissertation is organized as follows: Chapter 2 introduces the Opnet environment, by describing the elements and configurations used through all the tests, as well the users' behaviour different profiles. Chapter 3 presents the obtained performance for the implemented Campus scenario, while varying conditions like the number of users and users' behaviour. This chapter also concerns about testing hypothetical scenarios for determining the network performance for different levels of utilization, while guaranteeing the expected QoS levels, and providing alternatives in the scope of network reengineering. In Chapter 4, a mathematical model that based on existing measurements infers the future network QoS parameters will be verified for the Campus scenario.

2 Opnet Project Implementation

2.1 *Introduction*

In this work, different scenarios are analysed, covering variants of LAN’s and WLAN’s, allowing the study of distinct networks’ behaviours and features. The main studied scenario is in a Campus scale, being one of the goals the study of a specific Campus network behaviour, namely the Aveiro University Campus. This was done the increasing the number of users and varying the complexity of the scenario due to features like mobility, applications used and users’ roaming.

This chapter will focus on describing how the Opnet project was built, referring the most relevant steps for each of the purposed analysis, in a simple and synthetic way, and listing the elements used for building it as well as its respective settings. Also depicted are the different user profiles, and to conclude the collected statistics for the performance analysis will be covered.

2.2 *Components*

The scenario was built mostly using custom equipment, and not devices from a specific vendor (only the server has a specific brand), as no information was obtained regarding this, and because the final goals don’t demand such level of detail. Opnet has 3 main types of elements: node models, link models and demand models. The list of elements used to build the Opnet project is presented.

Link models

For the links that require larger bandwidth, that connect the multiple departments and the server, the used link was 1000Base-X. For single users and the wireless access point, connected in a star topology to the switch, the selected link was 100Base-T, enough for dealing even with the most demanding applications.

Demand Models

In order to collect the average round-trip time between each department and the server, it was necessary to use the following demand model:

- IP Ping Traffic Flow (IP_ping_traffic)

Node Models

The node models include all devices like workstations, routers, or servers, and configuration boxes like users' profile and mobility configurations. The various types of node models integrated in the scenarios are now listed:

- Ethernet server → represents a server node with server applications running over TCP/IP and UDP/IP. Supports one underlying Ethernet connection at 10 Mbps, 100 Mbps or 1 Gbps. Data is exchanged between it and each user. The selected server was HP 9000 rp7420-16: 8 CPU, 2 Cores per CPU, 1000MHz, HP/UX System, powerful enough to support the amount of operations associated with a Campus-sized network.
- Ethernet Switch (16, 32 or 64 ports) → represents an Ethernet switch supporting 16 (32 or 64) Ethernet interfaces and implements the Spanning Tree algorithm. Used to distribute the Internet to all users (which maximum number per department never exceeds 20, in the Campus scenarios, and 40, in the QoS scenarios) and to connect each department.
- Ethernet Workstation → represents a workstation with client-server applications running over TCP/IP and UDP/IP. It supports the same type of links as Ethernet server. These nodes are known as the fixed users. The reason for using this node instead of the Ethernet IP station is that the last doesn't allow the use of user profiles.
- Wireless LAN Workstation → represents a workstation with client-server applications running over TCP/IP and UDP/IP. It supports one underlying WLAN connection from 1 Mbps to 11 Mbps. These nodes are known as the mobile users.
- Wireless LAN and IP Ethernet router → represents a wireless LAN based router with one Ethernet interface. Distributes internet to mobile users.
- Ethernet Bridge → represents a wireless LAN based bridge with one Ethernet interface. Used to replace wireless LAN and IP Ethernet routers when using roaming.
- Profiles Configuration → used to create user profiles, which can be specified on different nodes of the network to generate application layer traffic. The applications defined in the Application Config objects are used by this object to configure profiles. Allows the specification of the traffic patterns that rules the applications as well as the configured profiles.
- Application Configuration → Used for specifying ACE Tier Information, Application Specification and Voice Encoder Schemes. The second option allows the specification applications using available application types, and was edited for creating the desired profiles.
- IP Attributes Configuration → Defines attribute configuration details for protocols supported at the IP layer. The different "ping" option settings that individual hosts/routers in the network can use to determine connectivity to the specified destination are defined at IP Ping Parameters. Included for configuring the measurement of the round-trip time between specific nodes and the server.
- Mobility Configuration → Defines mobility profiles that individual nodes reference to model mobility, and controls the movement of nodes based on the configured parameters. The chosen profile can be applied using "Topology – Configure Mobility Profiles on Selected Nodes…".

These node models used are presented in figure **2.1**.

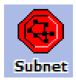
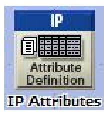
Node	Object Palette name	Figure
Ethernet Server	ethernet_server	
Ethernet Switch (16 ports)	ethernet16_switch	
Ethernet Workstation	ethernet_wkstn	
Wireless LAN Workstation	wlan_wkstn_adv	
Wireless LAN and IP Ethernet Router	wlan_ethernet_router	
Ethernet Bridge	Wlan_eth_bridge	
Subnet	Subnet	
Applications Configuration	application config	
Profiles Configuration	profile config	
IP Attributes Configuration	IP attribute config	
Mobility Configuration	mobility config	

Figure 2-1 – Nodes List

2.3 *Simulated Network*

University of Aveiro main Campus is located in Santiago, Aveiro, Portugal, and its infrastructure includes buildings for each department, plus the Superior Health School (ESSUA), as well fundamental facilities like the shopping area, where the coffee shop or the copy center are located (MALL), as well as the library, the sports facility (SPORTS), the rector house (MAIN) and the students' residences (RES1 and RES2). The real network size is about 500 m per 800 m (height per width). The Campus map is split in figures 2-2 and 2-3.

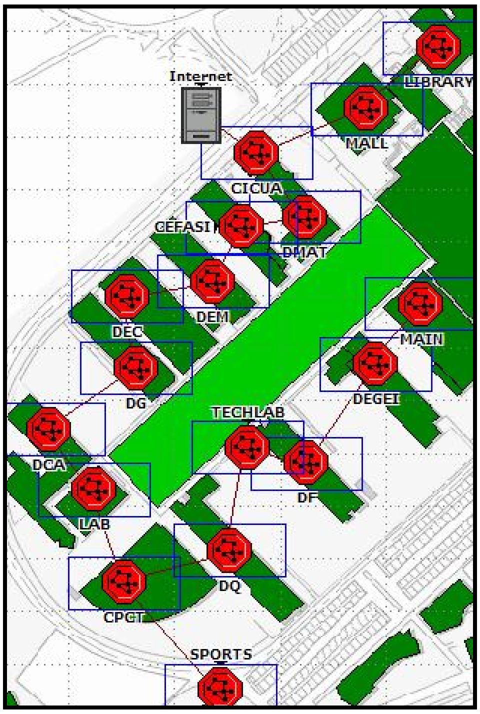


Figure 2-2 - Scenario A

The studied Campus network dimensions built at the simulator were intended to be fairly close to the real ones, so, in order to achieve that, and to better control the geographical positions of the whole Campus infrastructure, after creating an empty scenario, a background map was introduced the following way:

View -> Background → Add Image →Import Background Image

Concerning the network structure, the option was to represent the whole Campus by a bridged Ethernet network, where the buildings are connected to each other according to a tree topology, ensuring a loop free network. Each department is connected to the backbone through a main switch, and is symbolized by an Opnet subnet node, simplifying the scenario and nodes handling and giving it a friendlier look. Inside each of the subnets, the departments' switch was linked to a wireless router (access point) and a variable number of users through an Ethernet star topology.

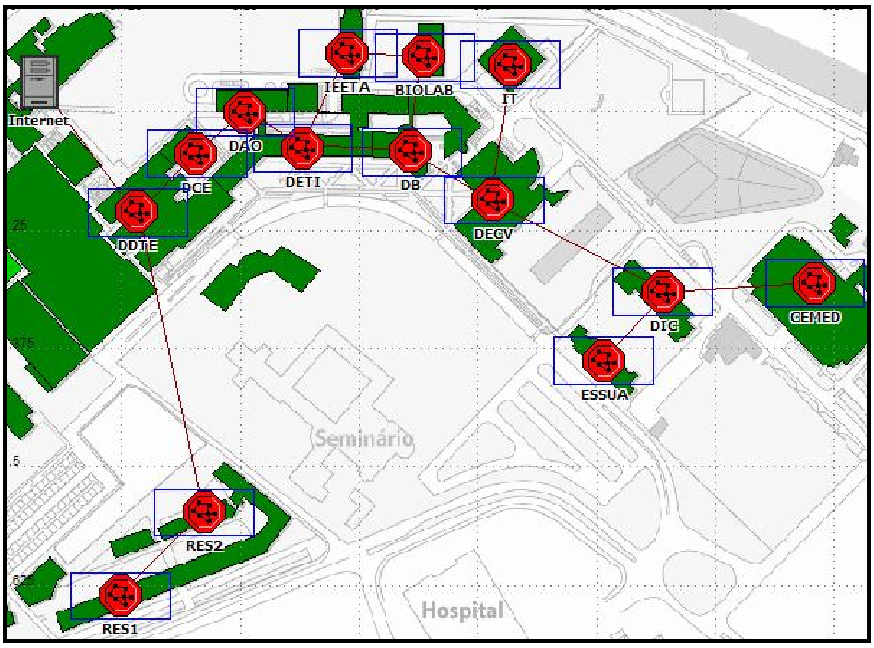


Figure 2-3 – Scenario B

The initial scenario - *Campus scenario* - contained the whole network structure, but the necessary time for running the simulation was far above the desired (about 20 h for profile 3); the reason for this is that the simulation time grows exponentially with the number of nodes. Driven the fact that the Campus contained 31 buildings, the choice was that all the following simulations were done using a quicker and computationally lighter way, by splitting the scenario into 2 smaller scenarios, one with 17 buildings (scenario A), and another with 14 (scenario B) buildings. This saved valuable time and allowed doing more tests.

By doing the previous change, and in order to make the 2 scenarios network behavior closer to what it would be for a single scenario, it was necessary to include a background load in the main link (Internet ↔ Backbone) for each of the 2 scenarios. This load represents the traffic due to the other scenario that would be added to the main link if the whole Campus was being simulated, so this value was obtained according to the observed average throughput in the main link of the complementing scenario. In figures 2-2 and 2-3, the departments are represented by the named “buttons”, or subnets , and the squares around each department represent the dimensions that each one of them have in the scope of the network, so they all are considered to have the same area. In the same figures, the buildings are linked by 1000 Base-X links, which connect all the buildings and the server. The rest of the elements shown in these 2 scenarios are simply part of the included background map, so they have no effect in the simulation other than a better visual comprehension. As for figure 2-4, the wireless access point is included to be used as a reference point for obtaining the ping response time, or round-trip time from each department to the server, which is the demand model symbolized by the dashed line. The other elements (the users, the department switch, and the backbone switch) are immediately recognizable in the figure: The next part does a full description of the performed settings changes at the components (nodes, links and demand models), and differentiates each of the user profiles used through the scenarios.

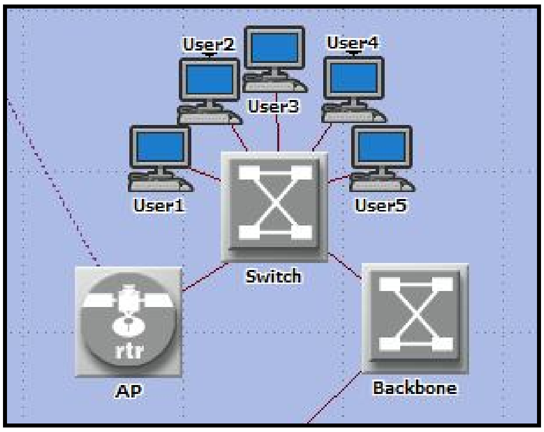


Figure 2-4 - Department structure on Opnet (for 5 users)

2.4 *Profiles and settings*

During the process of network planning and design, it is necessary to estimate the expected traffic intensity and thus the traffic load that the network must support. If a network of a similar nature already exists, then it may be possible to take traffic measurements from it and use that data to calculate the exact traffic load. However, as is more likely in most instances, if there are no similar networks to be found, the network planner must use forecasting methods to estimate the expected traffic intensity. This is the case for which the simulator comes to use: knowing the users traffic matrix, or behavior, the whole network behavior is predicted for such users. The used profiles are supposed to be close to real ones, though they were built simply using standard mathematical models for modeling the packet transfer distribution, leaving out the unpredictability of a real user.

One of the strongest barriers when starting using Opnet is acquiring the correct knowledge of how users' profiles configuration works. While Profile Config node models the associated applications, and allows configuring their and the profiles themselves start time, duration and repeatability, Application Config node is used to configure the applications processing, like average file size, inter-request time, ToS, send and inter-arrival time, etc. That is, it's possible to define the inter-arrival time of a packet, the inter-repetition time of that application and the repeatability of the respective profile, which may be difficult to assimilate. To simplify those concepts comprehension, an analogy can be done: imagine a big box, the Profile box, which represents a Profile in course, and can contain many equal medium boxes, the Application boxes, representing the number of repetitions an application is repeated inside the same profile; each medium box can contain many smaller boxes, the Packet boxes, representing the number of packets sent during the same application process. This example is shown in figure 2-5.

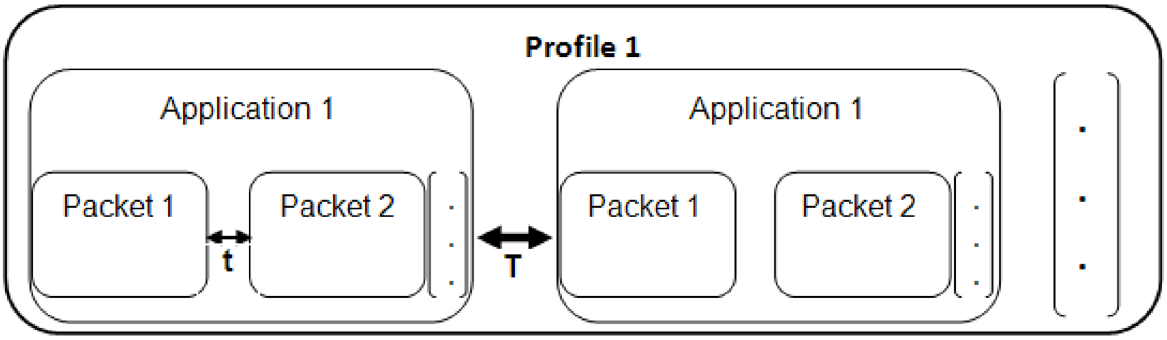


Figure 2-5 – Analogy regarding Opnet profiles and application configuration

The specifications used for the initial scenario, as well as the user profiles are defined below. The user profiles can be divided in 2 parts: the profiles used in the Campus scenario, and the ones used for the QoS evaluation chapter.

2.4.1 Settings

All the specifications, from the devices to the user profiles and applications configurations will now be described, as well as the reason for choosing each of them. This will hopefully provide a clearer view of the Opnet desktop, giving the novice user an overview of the most appropriate scenario building methods.

Ethernet Server

The following Ethernet Server attributes were changed, in order to support all applications used by the profiles, and for selecting the exact server model the following attributes were edited:

Applications – Applications Supported Services – All
Servers – HP 9000 Model V2200 4 CPU: 1 Core per CPU, 200 MHz, HP/ UX System

Wireless LAN Workstation

The following LAN workstation attributes were changed for setting the associated user and mobility profiles as well as the mobility trajectory:

Trajectory – VECTOR
Applications - Application supported profiles – Profile name – MobileUser
Mobility Profile Name – Depending on the user's position.

The *vector trajectory* is defined by a vector that points to a random direction, which defines the movement of the user; after reaching the mobility profile specified map limits, a new vector with a random direction will be associated with the movement, and so on.

Ethernet Workstation

The following Ethernet workstation attributes were changed for selecting the user profile:

Applications - Application supported profiles – Profile name – FixedUser

Each of the user profiles will be discussed in the next section.

Wireless LAN and IP Ethernet Router

No attributes were initially edited. The most relevant specifications related to the physical data transmission are shown:

• Wireless Protocol – IEEE 802.11g, at 54Mbps data rate
• Transmit power – 50 mW
• Power threshold – -95dBm

IP Ping Traffic Flow

This demand model is responsible for the ping inter-request times and repeatability, necessary for obtaining the round-trip times. The following IP traffic flow attributes were changed:

Ping Pattern – Repetition Configuration – Inter-repetition time – 60 s
Maximum Repetition Time – Unlimited

This demand model was set from each AP to the Internet server. Only for the scenarios without wireless AP's (for example, in the user profiles scenarios) it was set from the user to the server.

Links Configuration

The transmission and reception ports on all links were randomly set by the simulator.

Application Configuration

This node is responsible for defining each service that may be used by the workstations. Initially, default configurations were used, whereas the more relevant values were:

- FTP (heavy use) average file size = 50 Kbytes, with inter request time exponentially distributed with mean 360 s.
- Web browsing (heavy use) average page size = 1 Kbyte, with page inter-arrival time exponentially distributed with mean 60 s.
- Email (heavy use) inter-arrival receive and send time exponentially distributed with mean 360 s; send group size = 3, and email size = 2 Kbytes.
- Email (light use) inter-arrival receive and send time exponentially distributed with mean 3600s; send group size = 3, and email size = 500 bytes.

IP Attributes Configuration

This node is responsible for handling the IP ping traffic flow demand model, and default configurations were used.

2.4.2 User profiles

Before studying the behavior of the full network, each of the created user profiles was studied in order to assess the network behavior with their inclusion. The goal was to describe a typical user with a set of typical associated applications, where each user is represented by a different user profile. The modeled users include: a Light Internet user, simply using web browsing and mail services; a Medium Internet user, which uses FTP transfers besides the previous services; a Multimedia Internet user, a more actual approach by using VoIP calls; and a Heavy Internet user, where large transfers are needed, as a closer approach to nowadays P2P services. As for the QoS evaluation profiles, 3 profiles were created: Medium Internet user 2, Heavy Internet user 2 and Massive Internet user, for modeling networks suffering from high utilization or even congestion. Figure 2-5 shows the network topology used for the simulations.

As can be concluded, the users profiles vary from a very simple user with only mail and web browsing, to a very demanding type of user with videoconference, used in QoS analysis.

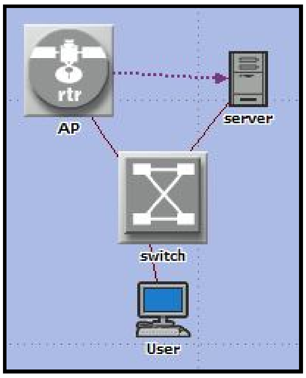


Figure 2-6 - Structure used for profile analysis

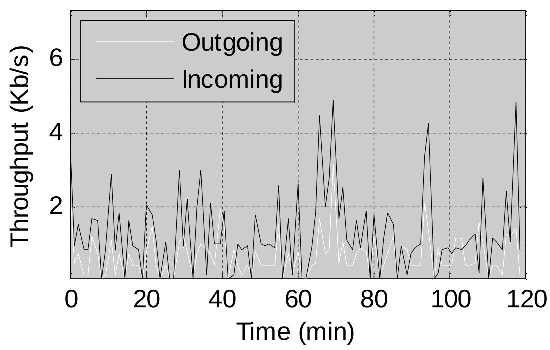
2.4.2.1 Profile 1 - Light Internet user

This user profile included heavy mail and web browsing as the demanded services, typical applications used by office secretaries, non-IT employees, etc. These generate low data rates on networks. The Profile Config attributes used at Opnet are the following:

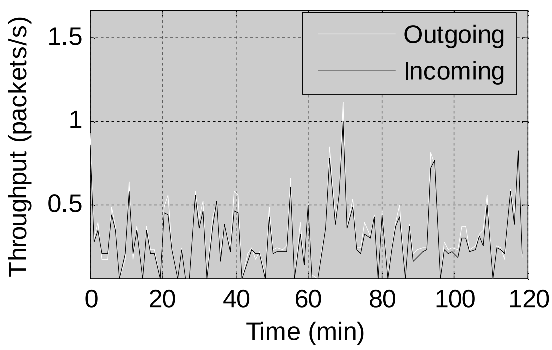
→ *Name - Web Browsing (Heavy HTTP 1.1)*
Start Time Offset – exponentially distributed with mean 10 s
Duration – End of Profile
Repeatability
Inter-repetition time – exponentially distributed with mean 300 s

→ *Name – Email (Heavy)*
Start Time Offset – exponentially distributed with mean 10 s
Duration – End of Profile
Repeatability
Inter-repetition time – exponentially distributed with mean 900 s

The obtained throughputs in Kbps and packets/s at the server-switch connection are shown in graphics 2-1 and 2-2, respectively.



Graphic 2-1 - Profile 1 throughput (Kb/s)



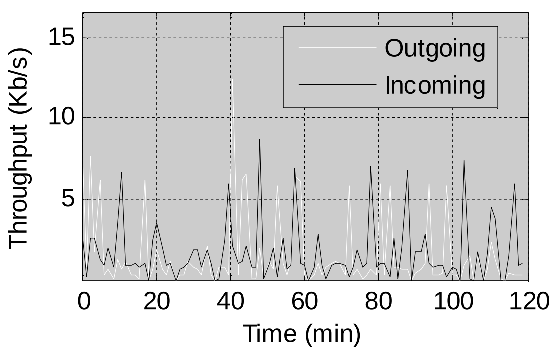
Graphic 2-2 – Profile 1 throughput (packets/s)

2.4.2.2 Profile 2 – Medium Internet user

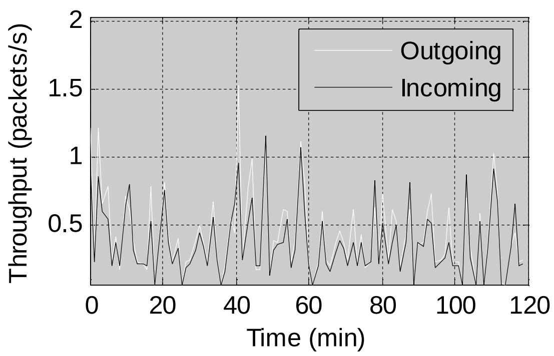
This user profile includes the File Transfer Protocol (FTP) service, beside mail and web browsing. It corresponds to a more active and common user, like a student, where nowadays FTP dedicated servers keep huge amounts of data, and users are willing to use the quickest way to obtain the needed contents like software, e-books, or multimedia files. FTP fits in the client-server model and runs exclusively at the TCP protocol, unlike the more recent P2P networks, which are commonly run under application layer protocols like BitTorrent and are typically used for connecting users via largely *ad-hoc* connections; nevertheless, the use of FTP for this profile should be viewed as the representation of any kind of file transfer. The additional Profile Config attributes were configured:

→ *Name – File Transfer (Heavy)*
Start Time Offset – exponentially distributed with mean 20 s
Duration – End of Profile
Repeatability
Inter-repetition time – exponentially distributed with mean 1200 s

Note that the receive/transfer rate was set at 50%, so the incoming traffic is expected to be approximately the same as the outgoing one. The results for Profile 2 are shown in graphics **2-3** and **2-4**.



Graphic 2-3 – Profile 2 throughput (Kb/s)



Graphic 2-4 – Profile 2 throughput (packets/s)

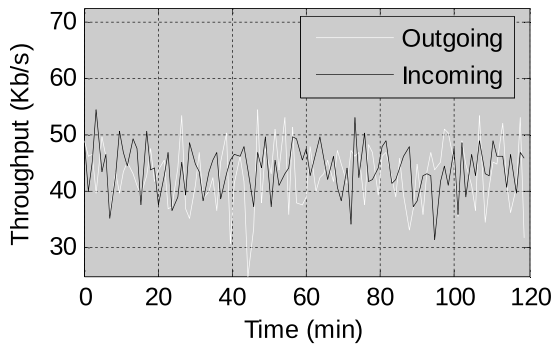
2.4.2.3 Profile 3 - Multimedia Internet user

When thinking about multimedia, one's brain immediately associates sensorial contents such as images, audio and video. But also combined with those is interactivity, which is a strong part in today's habits, and is associated to services like gaming, and particularly, VoIP voice calls. This profile is similar to the Medium internet users' one, with the inclusion of VoIP service that, even with the available audio processing technologies, represents a significant increase in the data rates. VoIP use has brought many benefits to users, merging voice and data applications, and has also liberated business processes; it has provided voice communications to everyone, everywhere, and over any device, and being a key service in actual networks, its use in Opnet should be studied. The following Profile Config attributes were added:

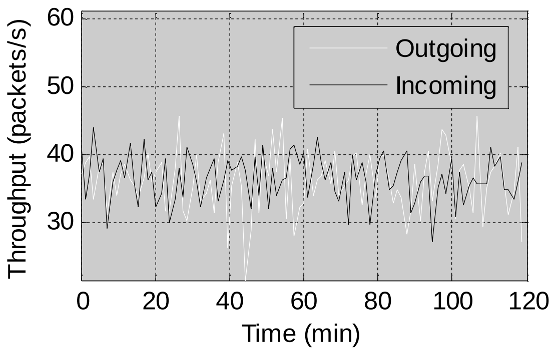
Application

→ *Name – Voice over IP Call (PCM Quality Call)*
Start Time Offset – exponentially distributed with mean 20 s
Duration – End of Profile
Repeatability
Inter-repetition time – exponentially distributed with mean 1800 s

The results for Profile 3 are shown in graphics 2-5 and 2-6.



Graphic 2-5 – Profile 3 throughput (Kb/s)



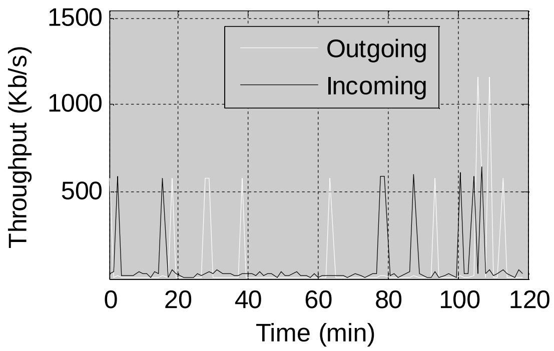
Graphic 2-6 – Profile 3 throughput (packets/s)

2.4.2.4 Profile 4 - Heavy Internet user

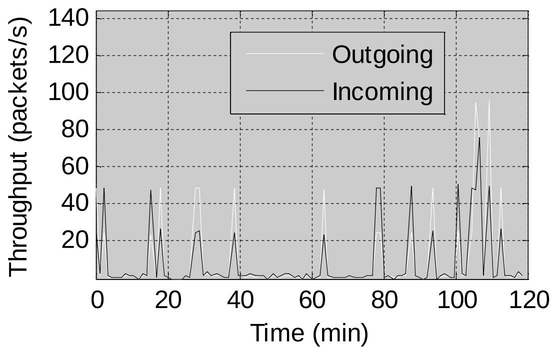
With American Internet Service Providers concerned about what they consider "abusive" use of internet by a small part of the users, as, according to one company, "5 percent of customers use more than 50 percent of the network's overall capacity", they are willing to take measures like bandwidth metering and sub charges cashing for users who exceed their bandwidth limits: something which has been up in many other countries for years, including Portugal. Bandwidth limitation is a hot theme, as critics of these measures think that "metering and capping network use could hold back the inevitable convergence of television, computers and the Internet", as said in New York Times online article, "*To curb traffic on the Internet,* *access providers consider charging by the Gigabyte*". The importance of such debate is indisputable, with millions of people radically changing their lives as all services are added an online possibility, like movies and TV streaming, videoconferences (whether for business or to keep up contact with the family), or participating in multiplayer online games. All these activities have one common factor: they spend large amounts of bandwidth.

This profile is based on the medium internet user profile, but considers a more demanding type of user which behavior needs to be studied. Still, by far this profile is not so bandwidth devouring as a frequent peer-to-peer user. An interesting statement was done by Cisco company reflecting that the increase in downloading and uploading habits is out of hand: "today's hog is tomorrow's average user".

Therefore, the FTP average file size for this profile is 5 MB and the average browsed page size is 100KB, corresponding to more actual values. VoIP services are not used, in order to decrease the simulation time. Again, the FTP service is used in order to represent such type of transfer as audio, video, or software download, common in a profile as versatile as the modeled user. The changes were done at the Applications Config node, and the results are presented in graphics **2-7** and **2-8**.



Graphic 2-7 – Profile 4 throughput (Kb/s)



Graphic 2-8 – Profile 4 throughput (packets/s)

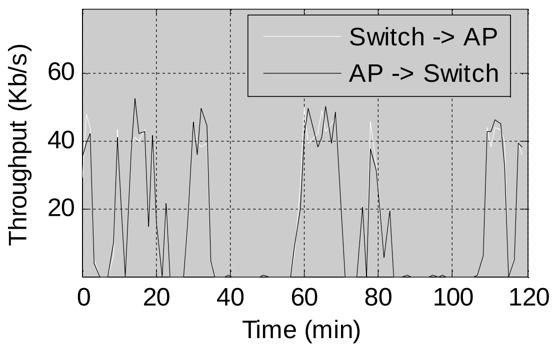
2.4.2.5 Profile 5 – Mobile Internet user

Mobile connectivity became a trend in the last years, with the consolidation of Wireless technologies over laptops and handheld devices like PDA's and 3rd generation mobile phones. The modeled profile was not intended to be very bandwidth demanding, so the services included were light email and VoIP (using PCM), while services like online messenger and IPTV weren't considered. Factors like the physical propagation method and mobility are important ones that need to be covered, reason why including such user profile is needed. For measuring the statistics the user was static; mobility will be included in later Campus scenarios.

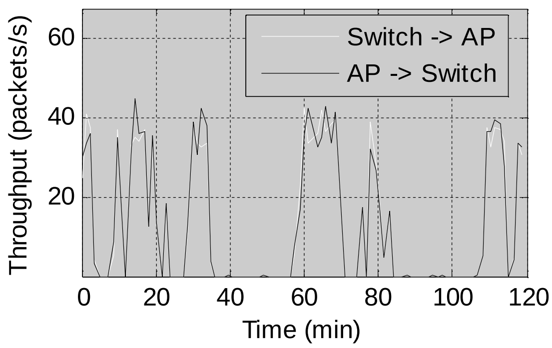
The additional Profile Config attributes were:

Profile Name – MobileUser
Applications
→ *Name – Email (Light)*
Start Time Offset – exponential (20)
Duration – End of Profile
Name – Voice over IP Call (PCM Quality Call)
Start Time Offset – exponential (20) s
Duration –End of Profile
Repeatability
Inter-repetition time – exponential (1800) s
Number of repetitions - unlimited
Start Time – constant (0) s
Duration – End of Simulation
Repeatability – Once at Start Time

The throughput was measured between the switch and the access point and the RTT was measured between the AP and server; the results are presented in figures 2-9 and 2-10.



Graphic 2-9 – Profile 5 throughput (Kb/s)



Graphic 2-10 – Profile 5 throughput (packets/s)

2.4.2.6 QoS Evaluation Profiles

In one of the scenarios of the QoS Evaluation chapter, where the goal is to study the service quality in more demanding scenarios, 3 new types of users were specifically created: Medium Internet user 2, Heavy Internet 2 and Massive Internet user. All these profiles were intentionally more demanding than the previous ones in bandwidth requirements, in order to study high links utilization scenarios, and the use of multiple users' profiles in the same scenario was also an interesting element of study.

- Profile A- Medium Internet user 2*:* consists of light FTP, heavy mail and heavy web browsing users, where FTP packet size is 1 MB and web page size is 100 KB.
- Profile B – Heavy Internet user 2*:* consists of heavy FTP (file size of 25 MB) and light web browsing (web page size of 50 KB) users.
- Profile C- Massive Internet user: consists of heavy videoconference and light browsing users. Videoconference properties are the following:

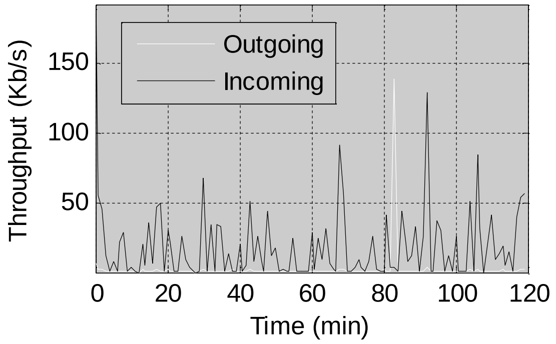
  Frame interarrival time information – 15 frames /s

  Frame size information – 128x240 pixels

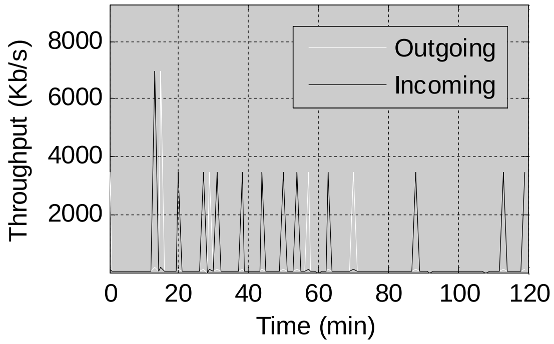
  Symbolic destination name – video destination

The inclusion of heavier file transfers and videoconference is a level headed decision, as these are telecommunications networks services of great importance, with a growing perspective for the future. Videoconference, particularly, will turn into a common service, as the distances created by nowadays constant mobility can only be overcome by the use of technology. IP based videoconference is just one of the multiple video based services, in pair with high quality multicast IPTV channels and IP based HDTV. With high speed internet connectivity becoming widely available at a reasonable cost, and video capture and display technologies cost decreasing, personal video teleconference systems composed of webcam, personal computer system, software compression and broadband Internet connectivity have become reachable for the most common users. Also, the availability of freeware (usually as part of chat programs) helped in turning videoconference easily accessible.

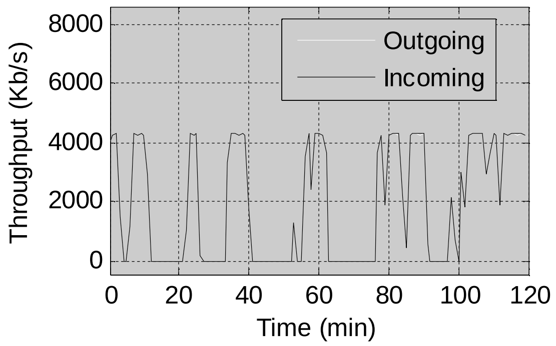
The integration of multiple profiles in the future scenario makes it closer to actual heterogeneous networks. For these profiles, each statistic was collected 120 times, one per minute; the throughput results are shown in graphics **2-11** to **2-13**. The next section describes the collected statistics, and the reasons for using them.



Graphic 2-11 - User throughput for Profile A (Kb/s)



Graphic 2-12 - User throughput for Profile B (Kb/s)



Graphic 2-13 - User throughput for Profile C (Kb/s)

2.5 *Collected Statistics*

A set of network simulation statistics was collected for each scenario. The traffic throughput is one of the most important network statistics for a network manager. Therefore, it was collected in all scenarios. This statistic is the amount of digital data per time unit that is delivered over a physical or logical link, or that is passing through a certain network node, and is usually measured in bit per second (bps) or data packets per second. It also corresponds to the digital bandwidth consumption, and was obtained for the existing link between two nodes, the department's switch and the backbone switch, because analyzing these links gives more information about the network load than the study of the users' link throughput. The incoming throughput is considered to flow from the backbone to the switch, and the outgoing throughput is considered to flow from the switch to the backbone.

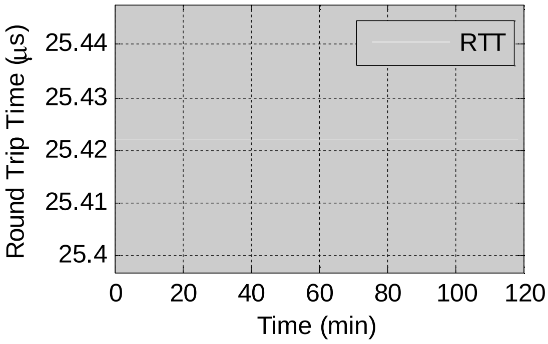
For the profiles study, and further for the Campus network study, one QoS parameter was also studied: the ping response time from a user to the server, using the IP ping traffic flow model between the departments' AP and the server, representing the average round-trip delay time (RTT) for each department. This statistic directly affects the throughput, and is the time required for a packet to travel from a specific source to a specific destination, and back again. In this context, where client-server applications were used, the source and destination always represent a user-server pair.

In the QoS evaluation section, the voice application packet end-to end delay, call jitter and link utilization were also collected, in order to do a deeper analysis of the quality obtained with the VoIP service. The end-to-end delay is the time taken for a packet to be transmitted across a network from source to destination. Jitter, according to Opnet definition, can be seen this way: if two consecutive packets leave the source node with time stamps t_1 and t_2, and are played back at the destination node at times t_3 and t_4, then jitter = $(t_4\text{-}t_3) – (t_2\text{-}t_1)$. So, a negative jitter indicates that the time difference between the packets at the destination node was less than that at the source node. As for the utilization, is the link occupied percentage..

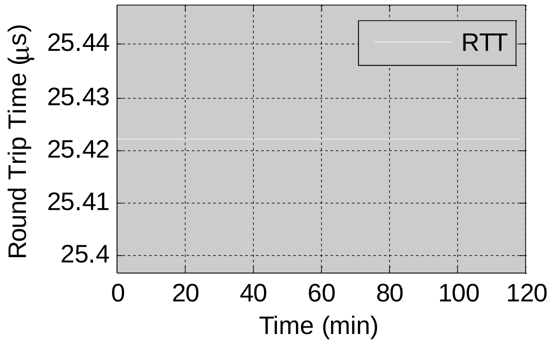
Regarding the simulations, the simulated time was 2 hours, and 100 values were collected for each statistic (one value per 72 seconds), except in the cases where another sampling frequency is clearly expressed.

2.6 *Profiles results*

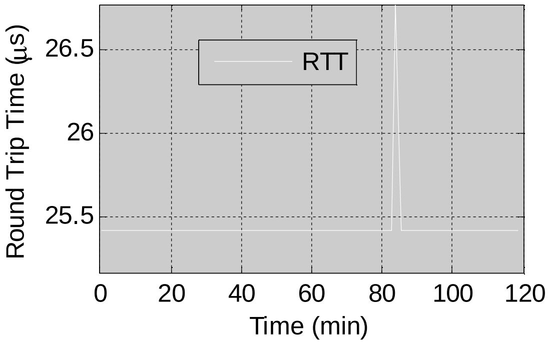
The round-trip time values didn't vary significantly for different users' profiles. This statistic proved to be independent of the used applications, as the biggest average RTT time was observed for the mobile user. This also means that the packet traveling time is not only proportional to the distance but also depends on the signal propagation method, which for that specific user is wireless. The results for each of the profiles are shown at graphics 2-15 to 2-19. The peaks that occurred at the multimedia and heavy profiles are unexpected, as the same didn't occur for more active users - the profiles created for the QoS study. These profiles presented a small increase comparatively to the others, explained by the use of a slightly different scenario, where the distance between the users and the server was influent. In resume, for links with low utilization levels, the decisive factors for the data transport times are the physical propagation method and distance.



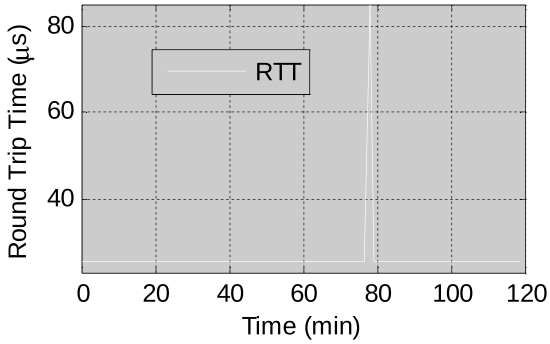
Graphic 2-14 – Profile 1 user round-trip time (µs)



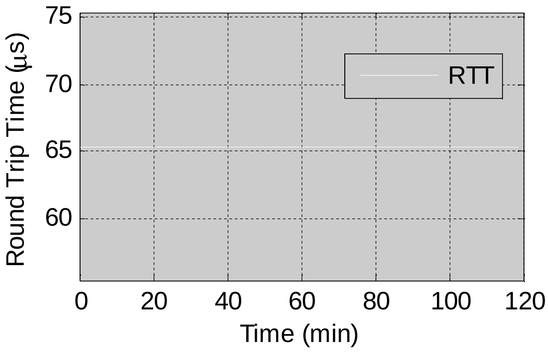
Graphic 2-15 – Profile 2 user round-trip time (µs)



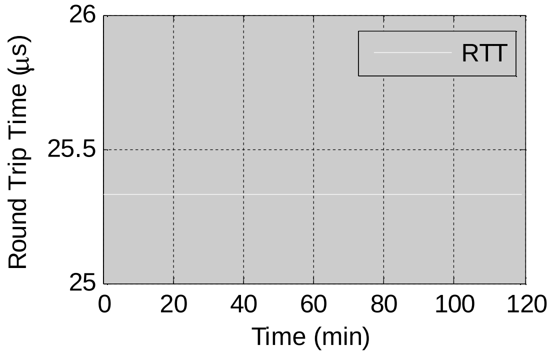
Graphic 2-16 – Profile 3 user round-trip time (µs)



Graphic 2-17 – Profile 4 user round-trip time (µs)



Graphic 2-18 - Profile 5 user round-trip time (µs)



Graphic 2-19 – Profiles A, B and C round-trip time (µs)

2.7 *Conclusion*

In this chapter, the developed project in Opnet was introduced, describing the configurations used and presenting the user's profiles settings and obtained results for the contemplated QoS parameters. The next chapter introduces the use of Opnet for real size scenarios and appropriate study cases in the scope of network management.

3 Simulation Scenarios

3.1 *Introduction*

In this chapter, Opnet tractability and usefulness for obtaining a Campus network performance is evaluated. In the first part, real Campus scale scenarios are modeled, starting with the baseline settings previously presented in section 2.3, and obtaining the consequent scenarios in a “what if” ideology. The second part of this chapter focuses on QoS study, especially for VoIP services, and several voice QoS parameters of voice applications are analyzed.

3.2 *Full Campus Simulations*

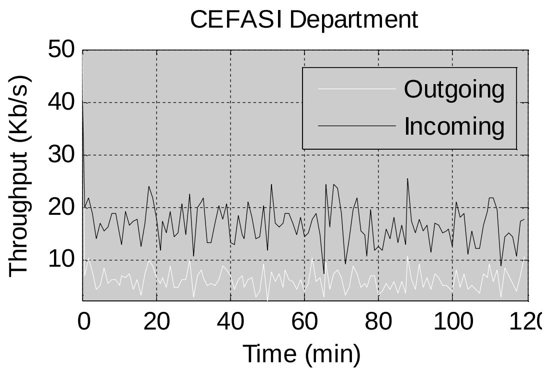
In this part, Opnet ability to approximately simulate an entire Campus network is studied. The load in the network was verified while varying the user profiles, by analyzing the ping response times between the server and the access points. Further on, more complex mechanisms were added to the network, looking forward to test more Opnet’s functionalities, such as wireless connectivity, mobility profiles and the implementation of users’ roaming. The next section will give some suggestions for an effective use of Opnet towards building the desired scenario. This is expected to work as a guide for anyone with networking basics who’s starting to use Opnet for similar tasks to the ones focused in this project and pretends to turn a hypothetical scenario into a functional enough one in Opnet, whether a full existing network, or the impact study of a specific structural decision, or for protocol study. Regarding this, a list of suggestions is presented in Appendix **A**, intending to provide beginners with valuable knowledge that may prevent most simulation failures and scenarios that defer from the desired. The next section will discuss the different Ethernet LAN scenarios studied.

3.2.1 Ethernet LAN

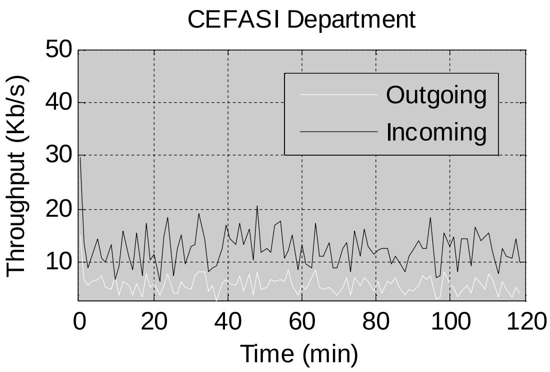
This part refers to networks simulations where users are exclusively of the Ethernet type. The throughputs at the switch-backbone link from one of the departments from each scenario are observed, as a reference for all the Campus scenarios. In some of the cases, the network is studied for 5 and 10 users per department, though, the ideal and more realistic solution would be to have an actual estimation of how many students are usually connected at each of the access points, in order to differentiate each department, and apply those values in the simulation. However, as some of the departments would present a high number of nodes, leading to higher computational and time demands, such method wasn't used. Therefore, in each scenario the same number of users was applied for all departments, also simplifying the analysis process, allowing direct comparisons when increasing the number of users.

3.2.1.1 Scenario 1 – Light internet user profile

This case was implemented in two ways: using a unique scenario and dividing the network into scenarios A and B (see figures **2-2** and **2-3**). The results for both ways are compared. All the other obtained results can be consulted at Appendix B. The profile used for the users was Profile 1 - light internet user profile, so low data rates and link utilizations are expected. The background loads used at the main links of the divided scenarios simulations were 176.000 bps of incoming traffic and 81.000 bps of outgoing traffic for scenario A, and 210.000 bps of incoming traffic and 97.000 bps of outgoing traffic for scenario B. The graphical results were obtained for CEFASI department from scenario A and BIOLAB department from scenario B, but for describing each of the profiles, the reference was the throughput in Kb/s from scenario A CEFASI department. This department's throughput in packets and all the graphics obtained for BIOLAB department from scenario B are provided in Appendix B.1. The throughputs for the 2 methods are shown in graphics 3-1 and 3-2, where can be seen that the transferred rates at the unique scenario were slightly higher.



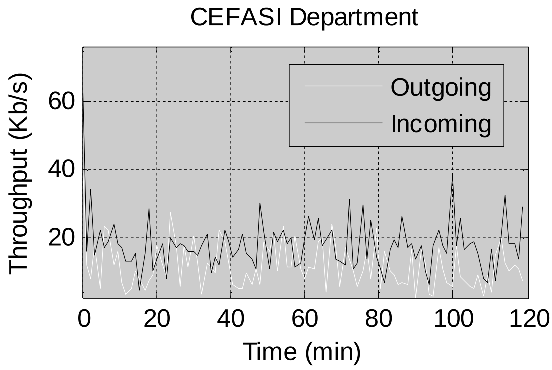
Graphic 3-1 – Scenario 1 throughput (kb/s) for unique scenario



Graphic 3-2 – Scenario 1 throughput (kb/s) using scenario division

3.2.1.2 Scenario 2 – Internet medium user profile

This and posterior scenarios were simulated using the scenario division, in order to economize simulation time, as explained before. The used profile for Ethernet fixed users is Profile 2 - medium internet user profile, which should lead to an increase in the network loads, due to the FTP use. The background loads used were 265.000 bps of incoming traffic and 170.000 bps of outgoing traffic for scenario A, and 330.000 bps incoming traffic and 210.000 bps outgoing traffic for scenario B. This profile' throughput is shown in Graphic 3-3.



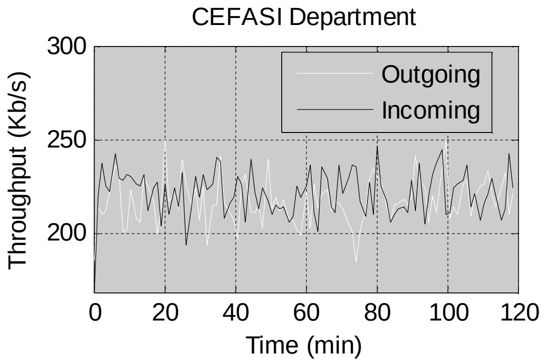
Graphic 3-3 – Scenario 2 throughput (kb/s)

3.2.1.3 Scenario 3 – Internet multimedia user profile

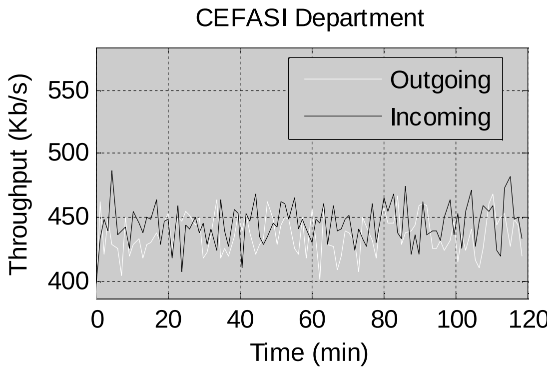
The network in this scenario presents users with a multimedia profile, which in nowadays networks is reflected in the traffic unpredictability, making it difficult for network managers to detect peak times, and being possible for a network to crash due to overflow. This case was simulated for 5 and 10 users per department, allowing the relation between the number of users and the throughput values to be observed. The used profile is Profile 3 - multimedia internet users' profile, and consequently major increases in the data rates are expected.

5 Users: The background loads for scenario A were 2.600.000 bps for both incoming and outgoing traffic, and for scenario B were 3.600.000 bps of incoming and outgoing traffic. The resulting throughput for CEFASI is shown in Graphic 3-4.

10 users: The background loads for scenario A were 5.300.000 bps for both incoming and outgoing traffic, and for scenario B were 7.500.000 bps of incoming and outgoing traffic. Graphic **3-5** shows the results for CEFASI department.



Graphic 3-4 – Scenario 3 throughput (kb/s) for 5 users



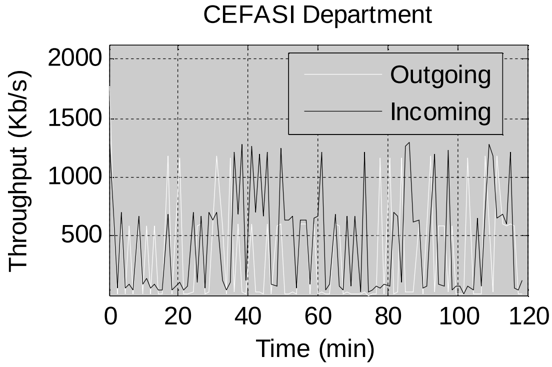
Graphic 3-5 – Scenario 3 throughput (kb/s) for 10 users

3.2.1.4 Scenario 4 – Internet heavy user profile

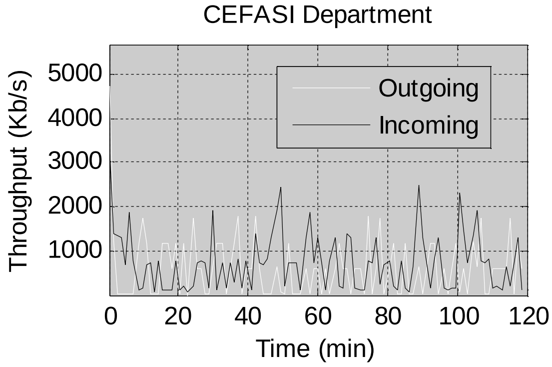
Looking forward to continue the users' traffic demand' increase criteria, it made sense testing more realistic and modern traffic models. The standard FTP file size was only 50 Kbytes and the web page properties was varying between 500 bytes and 2 Kbytes, so in these profile the FTP file size was updated to 5 Mbytes and the web browsing page properties changed to 100 Kbytes.. Still, these values could be surpassed by today's peer-to-peer applications users, or video and audio streaming, but to use such values is not one of the actual tasks. The network was studied for 5 users, 10 users and 20 users per department.

5 Users: The background loads for scenario A were 5.200.000 bps of incoming traffic and 4.400.000 of outgoing traffic, while for scenario B the values were 6.500.000 bps of incoming traffic and 5.500.000 bps of outgoing traffic. Graphic **3-6** shows the throughput values for CEFASI department.

10 Users: The background loads for scenario A were 10.500.000 bps of incoming traffic and 9.000.000 of outgoing traffic, while for scenario B the values were 13.500.000 bps of incoming traffic and 11.200.000 bps of outgoing traffic. The results for one of the departments are shown in Graphic 3-7, where unlike for 5 users per department, fewer and more noticeable peaks are watched. The study for a bigger number of users is appropriate, and is expected to bring even more distinguishable peaks, as in real networks, where the number of connected users can vary largely during time evolution.



Graphic 3-6 – Scenario 4 throughput (kb/s) for 5 users



Graphic 3-7 – Scenario 4 throughput (kb/s) for 10 users

20 Users: For this number of users, the Ethernet switches were replaced for 32 ports switches, and some of the departments presented insignificant values of throughput during all the simulation, with all of its users having low traffic. This problem couldn't be surpassed using the available methods, like replacing the server for a more powerful one, or replacing the switches, links or even the users, and for these reasons the results were discarded. The departments in which this happened were: CEFASI, CICUA, DF, DMAT, MALL and DEM departments from scenario A, as well as DIC department from scenario B, which means the scenario's load limit was at 12, 13 departments, or 240 to 260 users.

3.2.2 Wireless Ethernet LAN

These scenarios present a network with both Ethernet fixed and wireless users, in order to compare the network behaviour with the previous scenarios. The inclusion of wireless processes meant longer simulation times, as the processes involved are necessarily more complex. The changes included comparatively to the previous scenarios, other than just adding mobile users, were raising the values per statistic from 100 to 120, to get exactly one statistic for each minute simulated, and the setting of mobility profiles for each user. Each mobility profile corresponds to a geographical area in which the user can move, and the configuration was done the following way:

Topology – Random Mobility – Set Mobility Profile

Then, by selecting the Mobility Configuration and editing the desired mobility profile it was possible to delimitate each profile corresponding area. Two different scenarios were studied: one where mobile users are connected to the same access point during all the simulation time, and another where mobile users are added the roaming mechanism.

3.2.2.1 Scenario 5 – Wireless Network

The users profile is Profile 1 for fixed users and Profile 5 for mobile users, and this scenario was studied for 1 wireless user per department, where each user is connected to one of the departments' access point, and then for 3 wireless users per department. The transmit power for both the AP's and the mobile users was 0.001 Watt, and the mobility profiles are the following:

Mobility Configuration

1) Scenario A
   Random Mobility Profiles
   1) *Profile Name – North (x = [150…450]m and y = [50…300]m)*
   2) *Profile Name – Centre (x = [50…450]m and y = [300…450]m)*
   3) *Profile Name – South (x = [55…350]m and y = [450…700]m)*
2) Scenario B
   Random Mobility Profile
   1) *Profile Name – North (x = [0…625]m and y = [0…300]m)*
   2) *Profile Name – East (x = [500…1000]m and y = [250…400]m)*
   3) *Profile Name – SouthWest (x = [0…500]m and y = [300…700]m)*

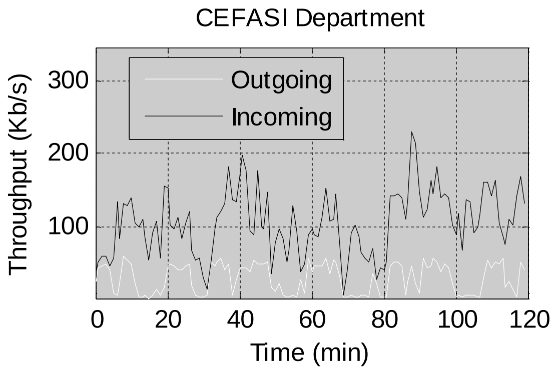
The user mobility profile used for each user is defined according to its initial position, so for example a user connected to CICUA department has the North mobility profile, and so on.

One wireless per AP:

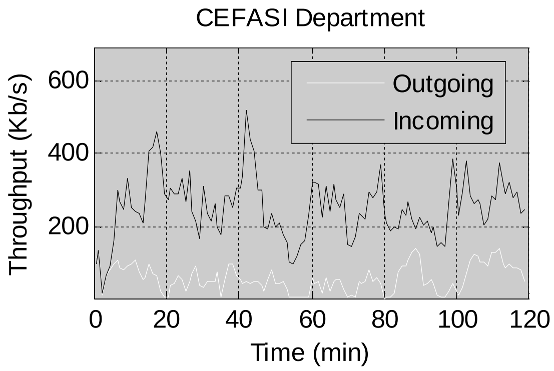
The background loads for scenario A were 450.000 bps of incoming traffic and 350.000 of outgoing traffic, while for scenario B the values were 490.000 bps of incoming traffic and 370.000 bps of outgoing traffic. The throughput associated with CEFASI department for this scenario is shown in Graphic 3-8.

Three wireless users per AP:

The background loads for scenario A were 860.000 bps of incoming traffic and 7600.000 of outgoing traffic, while for scenario B the values were 1.150.000 bps of incoming traffic and 1.030.000 bps of outgoing traffic. The results for this case at CEFASI department are shown in graphic 3-9.



Graphic 3-8 – Scenario 5 throughput for 1 mobile user per department (kb/s)



Graphic 3-9 – Scenario 5 throughput for 3 mobile users per department(kb/s)

3.2.2.2 Scenario 6 – Wireless Network with roaming

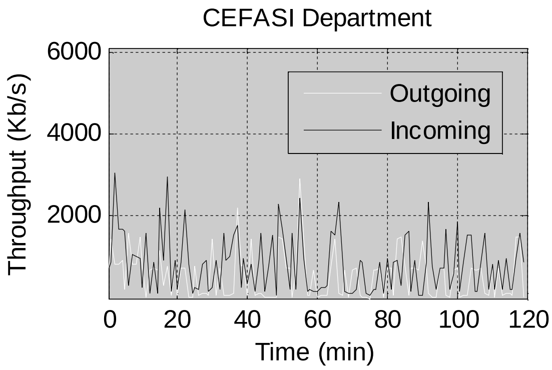
Initially, there was an attempt to activate this functionality by using wireless routers, but such feature wasn’t possible, as each router belongs to a different subnet. By using bridges, this problem was overcome, but it required the manual configuration of the network IP’s for the server and the wireless users. The wireless users and access points following attribute was changed for allowing this mechanism to work:

Wireless LAN – Wireless LAN parameters – Roaming Capability – Enabled

In order to increase the scenario’s accuracy, the users profile start time was made more variable, avoiding traffic and delay peaks at the beginning of the simulation, correcting one of the previous simulations flaws.

User Profile: Start time = exp(120) s

For this case study it was necessary to deactivate the mobility profiles limits, because the users transmit power didn’t allow them to roam through different AP’s in the originally defined areas: this way each user moved freely through the whole scenario. In this simulation, the number of collected statistics was 720, providing bigger detail on data, and making possible a posterior aggregation level of 6, to 120 points per statistic, as the previous simulations. For the simulation itself, the background loads for scenario A were 11.000.000 bps of incoming traffic and 9.000.000 of outgoing traffic, while for scenario B the values were 16.000.000 bps of incoming traffic and 14.000.000 bps of outgoing traffic. The selected profile for the fixed users was the heavy internet user profile. The throughput values are shown in graphic 3-10, where can be seen that CEFASI is a frequently used department.



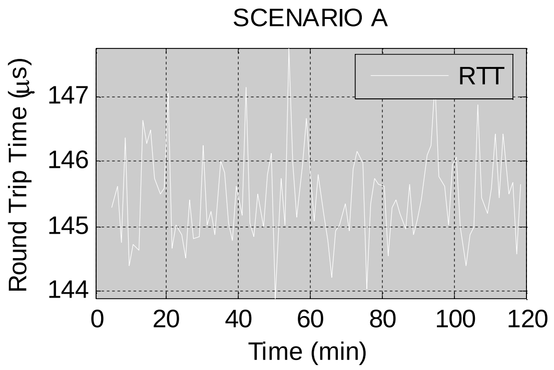
Graphic 3-10 – Scenario 6 throughput (kb/s)

3.2.3 Campus simulation results

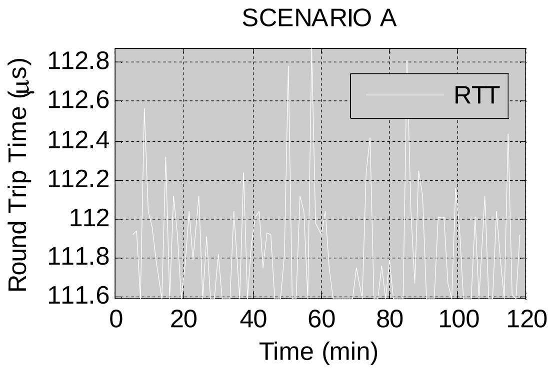
The results show the average round-trip time between all access points and the server for scenario A. The other collected results are presented in Appendix B.1.

Note that the first 4.8 minutes (corresponding to the first 4 points) were not included in the graphical representation of the round-trip times, as these values were very high due to the services request; this way it was possible to show the rest of the data in a more exact scale. The results for both the implementations of Scenario 1 are shown in graphics 3-11 and 3-12: it's important to compare the results using both methods, in order to be sure that the division option didn't negatively affect the goals for this chapter, which is simulating a Campus network in an approximately realistic way. The results for the rest of the studied scenarios are reflected in graphics 3-13 to 3-17. Scenario A' users reached higher round trip time values, possibly due to the larger number of nodes, even though smaller distances are crossed by the packets. This means that for a more significant number of users, there would be higher delays in departments like SPORTS or DQ.

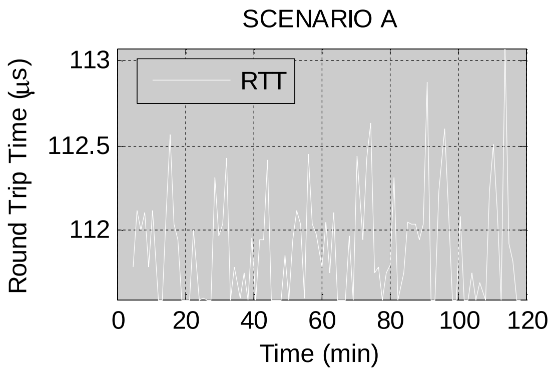
As can be seen, the RTT time obtained for a single scenario is bigger than with the split technique, but not significantly – an average of about more 35 μs. This can be a result of the way the background load is included, as an average value is included in the link, and not a variable traffic model, leading to smaller throughput peaks, and also smaller variance. It can also be seen that the RTTs didn't increase significantly for 10 users, and it was about 3 times smaller than the average for the roaming scenario. In general, the delays increased along with the amount of traffic and number of users as expected.



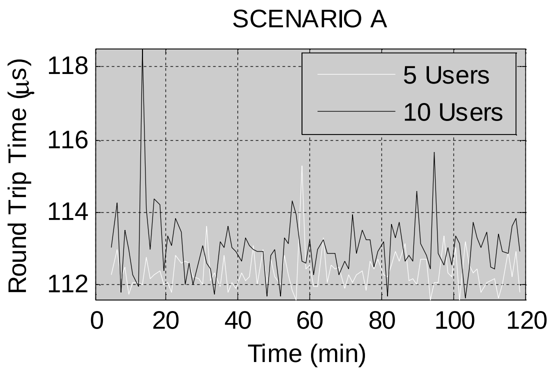
Graphic 3-11 – Scenario 1 RTT (unique scenario)



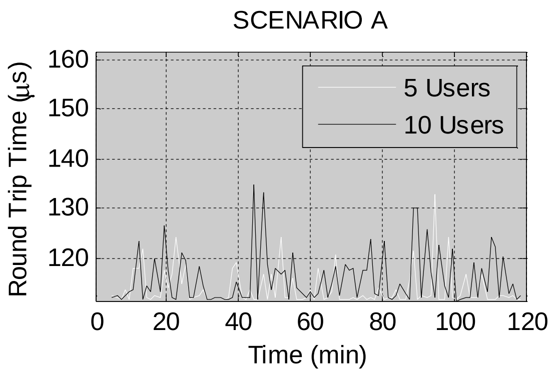
Graphic 3-12 – Scenario 1 RTT (split scenario)



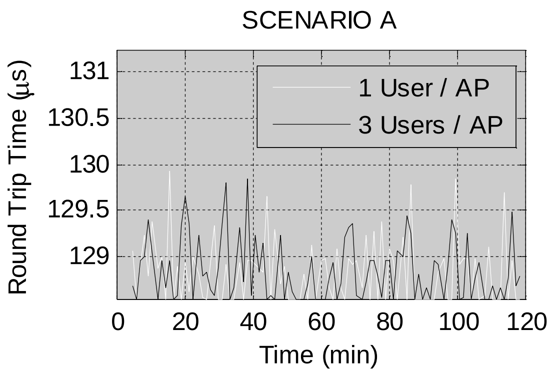
Graphic 3-13 – Scenario 2 RTT



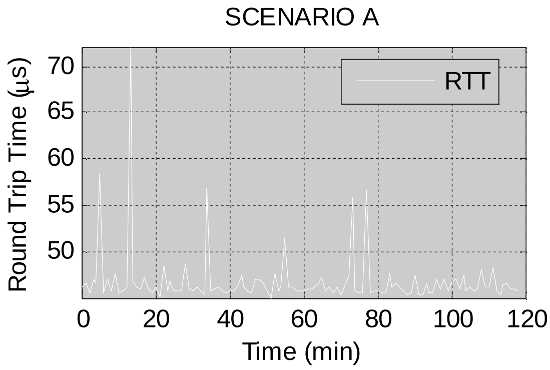
Graphic 3-14 – Scenario 3 RTT



Graphic 3-15 – Scenario 4 RTT



Graphic 3-16 – Scenario 5 RTT



Graphic 3-17 – Scenario 6 RTT

3.3 *QoS Evaluation*

With the growing popularity of multimedia services over internet, which demand high transmission rates and at the same time are very sensitive to delay and delay variation over the network, the concerns on respecting the required levels of quality also increased. This has lead to the creation of recent mechanisms and architectures like MPLS or DiffServ. Because in the previous sections the studied simulator functions were focused only on the networks traffic matrix variation, as well as in the handling of different services and users' mobility, another related area that is essential in networks managing and modelling is QoS control. This mechanism guarantees the required levels of performance desired in each type of application, and for that specific reason researching Opnet's capability to aid in obtaining valuable information on this field will now be the target. Therefore, the purpose will be to describe the experience of using Opnet for tasks related with measuring QoS levels, analysing the obtained results. For doing this, 3 case studies where created for providing distinct results that may help in network management.

Because simulating a scenario with the full Campus, or even half of it, would be so much time-costing, due to the high loads involved, a different and somewhat erratic way was used to run the simulations. This time, the network was simulated the following way: one initial scenario containing only one department was simulated, and then the collected averages throughputs values in both ways would be multiplied by the number of total departments minus one, that is, 30, and these values would be set as the background load of the link between the server and the department switch for the final simulated scenario, representing the whole Campus. The cost for this decision is undeniable: there would be a greater value in the results if there was the possibility of differentiating each department, either by the number of users, or by the users profiles themselves, but by doing so it was possible to test the scenario submission to very high loads and links utilization, without the dispense of an incredibly huge amount of time. The network can be observed in figure 3-1.

The dependence between the results and the user profiles is one important fact, though the objective was to observe the QoS levels for different levels of network saturation, and not according to the traffic models or user profiles.

Finally, it's important to keep in mind that the studied network is still the one initially purposed – the Aveiro University Campus, so all the realized tests goal was to help studying this network performance. More attention was given to the VoIP's QoS, as this service relevance is very significant nowadays, and the tendency is for it to be an essential service on future; therefore, quality defining parameters as end to end delay and jitter were controlled.

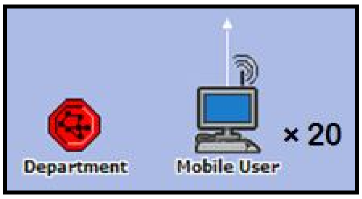


Figure 3-1 - QoS Evaluation scenario on Opnet

Settings

The VoIP service settings on the Profile Configuration node were modified for this chapter' simulations the following way:

Name – Voice Over IP Call (PCM Quality Call)
Start Time Offset – exponential (60) s
Duration – exponential (180) s
Repeatability – Interrepetition Time – exponential (300) s
Number of Repetitions – unlimited

The link used between the Server and the switch was of the 100BaseT type, in order to meet the intended goals of high utilization in the link. The users' profile is the heavy internet user profile, and all the simulations run for the section were done collecting 120 values for each statistic (one per minute).

3.3.1 Case study 1 – High link utilization network

The idea was to simulate a network where the main link was greatly used, with utilization near 100%, and afterwards verify the QoS parameters. For this scenario, the number of users per department was 38 fixed users (using profile 4) and 20 mobile users (using profile 5). The background loads were 93.379.000 bps of incoming traffic and 75.130.000 of outgoing traffic. The network structure is shown in figure 3-2, and the throughput values associated with the main link are shown in graphic 3-18. The rest of the collected results can be consulted in Appendix B.2.

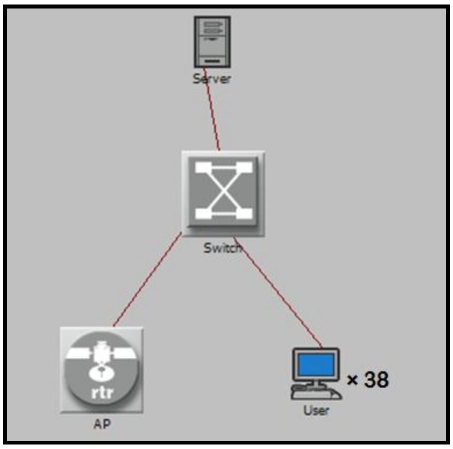
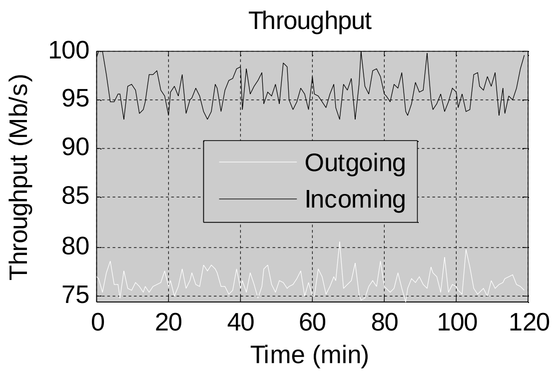


Figure 3-2 - Department structure for case study 1



Graphic 3-18 - Main link utilization for case study 1

3.3.2 Case study 2 – Overflowed network

For this case, the goal was to intentionally overflow the previous network, and verify the simulator network response through the obtained values for the various statistics. The number of users per department was 40 fixed users and 20 mobile users (using the previous profiles), and the background loads were 88.500.000 bps of incoming traffic and 102.000.000 of outgoing traffic. Again the results are graphically shown in Graphic **3-19**, and the network structure is shown in figure 3-3.

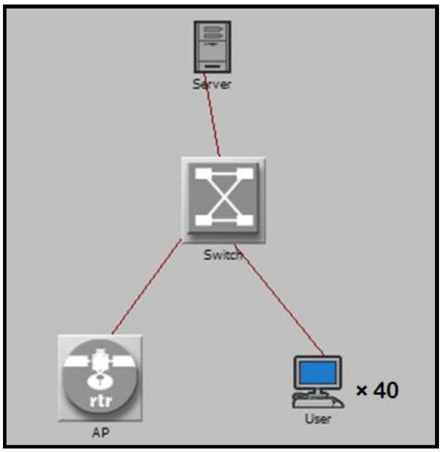
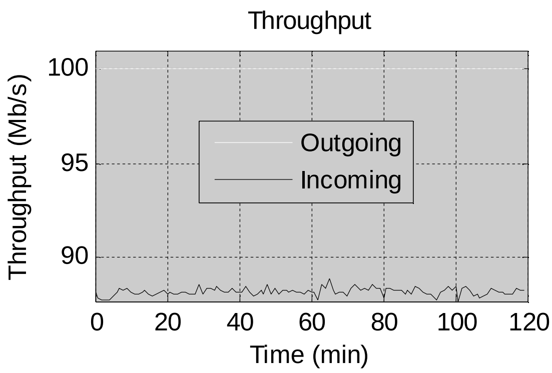


Figure 3-3 - Department structure for case study 2



Graphic 3-19 – Main link utilization for case study 2

3.3.3 Case study 3 – Network with multiple user profiles

As a network manager, the more efficient change to do would be upgrading the links between each department or, depending on the available resources, upgrading only the links closer to the server, as they suffer from larger utilization. In this example the link between the switch and the server was changed to 1000BaseX – for the full Campus, the changed link would also be the one coming from the server.

This scenario also implemented a more demanding and complex traffic model, as 3 types of profiles were used – see section 2.4.2.6. The number of users per department was 35 fixed users and 20 mobile users, where from the fixed users, 20 were using Profile A, 10 were using Profile B and 5 were using Profile C. The background loads were 431.910.000 bps of incoming traffic and 416.799.000 of outgoing traffic. The graphical results are shown in graphic 3-20, and the network structure is shown in figure 3-4.

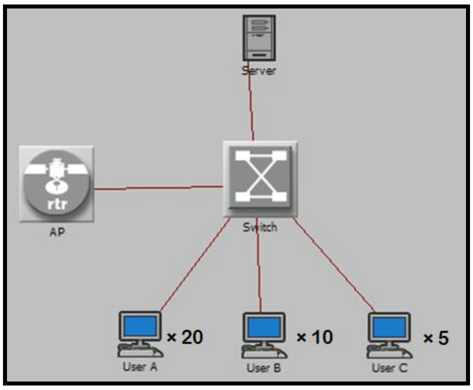
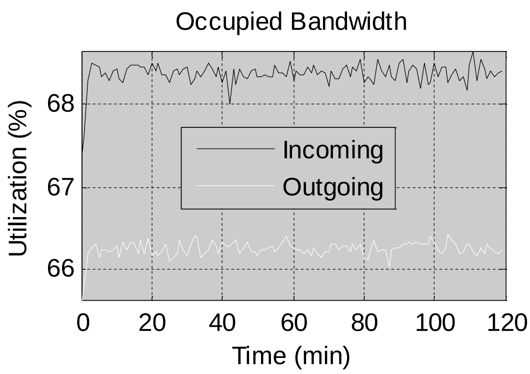


Figure 3-4 - Department structure for case study 3



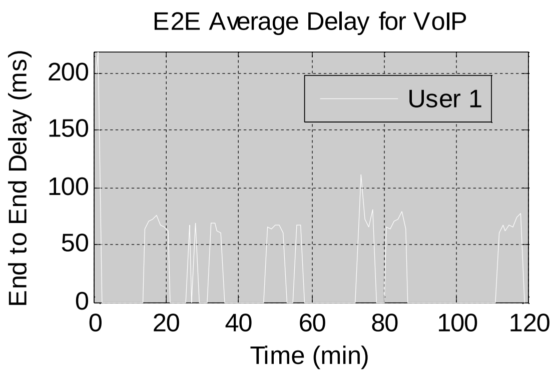
Graphic 3-20 – Main link utilization for case study 3

3.3.4 QoS evaluation results

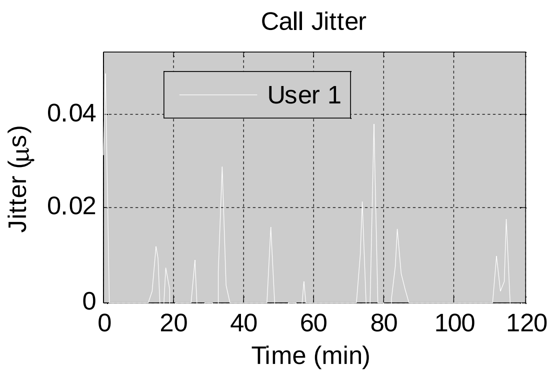
The results refer to one of the mobile users, and the purpose is to analyze VoIP's QoS. Additionally to round-trip time, the collected QoS parameters were voice call end-to-end delay and call jitter, in order to conclude the network affordability for these services. These results are shown from graphics 3-21 to 3-26.

Normally, the bigger the link utilization, the worse the end-to-end delay values are, but it's important to refer that Opnet only calculates the end-to-end delay based on the delivered packets, not considering the lost packets. Therefore, case study 1 presents higher values, as there are no blocked packets. As the end-to-end delay values were above the reference, 60 ms, quality in VoIP calls will be affected.

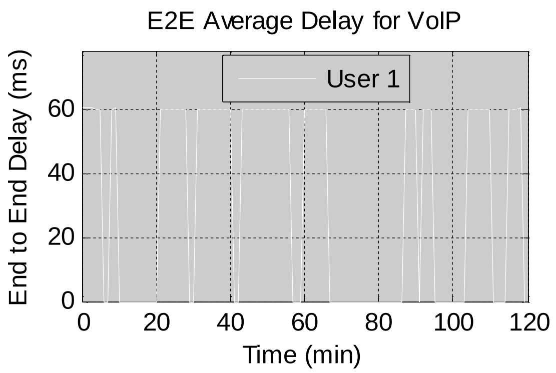
For Case study 2, even though the network was overflowed, the voice calls had the required levels of quality, driven its priority towards the other services. That explains the fact that the values were never above the 60 ms – the reference level for keeping a call with good quality. In case study 3, the throughput values were higher than on previous scenarios, but the main link was upgraded, so that prejudicial delays were prevented.



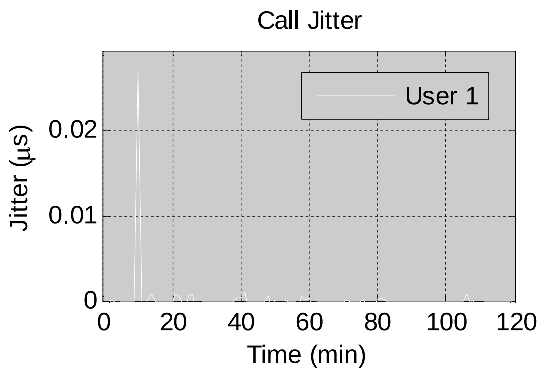
Graphic 3-21 – Case study 1 end-to-end delay



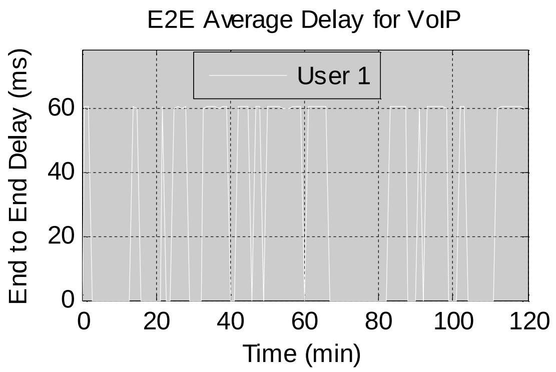
Graphic 3-22 – Case study 2 call Jitter



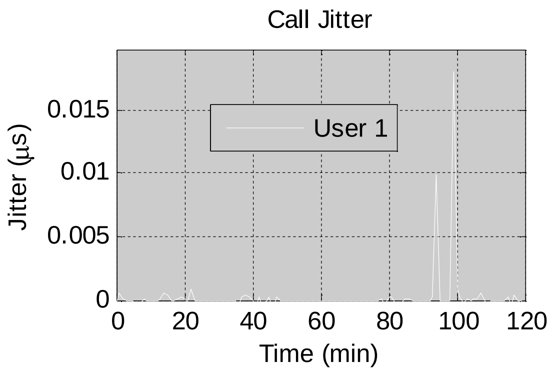
Graphic 3-23 – Case study 2 end-to-end delay



Graphic 3-24 – Case study 2 call Jitter



Graphic 3-25 – Case study 3 end-to-end delay



Graphic 3-26 – Case study 3 call Jitter

3.4 *Conclusion*

This concludes the first part of this project: the Opnet evaluation when working with Campus-sized scenarios. While managing to efficiently do several network modeling and simulation tasks, the program showed its downsides. The main negative aspect is its long learning curve, as the first attempts to use Opnet to build and simulate more complex networks can turn out to be frustrating, due to the lack of evidence in needing certain configurations in order to build the desired network, leading to unexpected errors when running the scenario simulation.

As for the results, two major options biased the results quality: the small variation of users during experiment and the use of a constant background load. Even using exponential distribution for modeling the applications repetitions for each user profile, the load in the network didn’t vary significantly like it does on real environments, where the number of users varies widely with time, as well as the type of services they use. This is correlated to the other problem, where the use of a constant background load of a very high value partially absorbs the variation noticed due to the rest of the network; this is the same as having a big part of the users always connected and generating the same load. Therefore, the use of a time modeled background load would benefit the results of a greater value and accuracy.

Opnet presented some problems when varying the scenarios’ conditions. For example, when trying to increase the number of users per each department from 5 to 10, the simple “copy-paste” operation of the nodes in one of the scenarios unexpectedly led to the simulation crash. The alternative was selecting *Topology* -> *Rapid Configurations*, and then choosing

Star topology and 10 peripheral nodes. The software presented unstable issues related with link failure. This happened for campus scenarios containing above a dozen departments, where the throughput at the switch of one or 2 departments would be almost null. Awkwardly, in some cases, the replacement of the links would repair the problem, which wasn't detected using the "detect link failure" option. The impact of this flaw frequently represented the loss of several hours, as the Campus-sized scenarios' simulations lasted from 2 to 30 hours. With the acquired experience, this kind of errors could be kept from occurring. The best way to prevent wasted time and simulations is to keep a cautious and critic attitude, by pausing the simulation after few simulated minutes, and analyzing the collected results so far at the top statistics table: If some link is presenting abnormal results comparatively to the others, a probable link malfunction is detected. For that reason, there was an attempt to transparently explain the best methods and "how-to's" that may keep readers from going through the same complications and spent time for obtaining the intended result in more effective scenarios.

In fact, most of the bugs noticed when running simulations can be avoided after acquiring the proper knowledge about the simulation tool, or at least their impact can be decreased by monitoring simulation results and using a trial and error approach. However, even with these learned techniques there were unsolved issues. When growing the number of users in the network to a great number (over 200), some of the users didn't download or upload any relevant traffic, revealing the switches limitation for dealing with such amount of traffic, as changing to a more powerful server didn't affect the results.

A decisive aspect when running the simulations was the level of detail. Detail is defined by the amount of settings done by the user, and Opnet proved to be widely configurable, at the various levels. The balance between detail and number of computational operations defines the quality of the simulation, as bigger detail brings more accurate results but spends more time. In general, the simulations didn't demand a high level of detail configuration for the intended goals, with many of the settings automated, simplifying the user job. The program is able to automatically set such details as IP addresses, BSS and port numbers, which is a great advantage for the user in terms of configuration time. The use of default devices when building the simulation network is great for studying general topologies, but it is also possible to use exact models and product lines, allowing a more strict study. For example, different routers handle traffic differently, as they may use different routing protocols.

The use of the GUI was generally helpful, but in some cases the availability of a command line would be preferred. Let's think about the third QoS evaluation scenario, Scenario C, where the goal was to grow the network by increasing the number of users per department. The possibility of quickly defining the number of users for all the subnets using a command would be an advantage, instead of doing so through the graphical interface. The increase in the number of users connected to a switch by copying the nodes is an unstable way because Opnet doesn't always update the IP tables when using the copy method, leading to application errors when trying to run the simulation. The most effective way found for doing so was deleting the whole subnet topology and using the Rapid Configuration method for a bigger number of peripheral nodes.

When dealing with link replacement, the lack of an option like "*Edit selected links*" was noticed, especially when needing to replace part of the links; the available alternatives were "*Edit similar links"*, or having to change each link properties individually.

For the results collection, a proposed feature would be a name filter, in order to separate the desired results from the rest. When studying the end-to-end delay from the users, for example, it would be convenient to export only results with the word "user", instead of also having to include the results from the server. As that filter was missing the results were exported and a script was responsible for the filtering, but for scenarios with a large number of users, the used program to export the results (Microsoft Excel by default) couldn't store all the results, due to the rows' limit.

The possibility of choosing the seed number is an advantageous option, because the bigger the number of simulations using different seeds, the higher the accuracy on the final results; nevertheless, all the simulation were run for only one seed, as repeating the simulations several times would compromise the realization of part of the simulations and goals.

In general, Opnet can be considered an efficient tool for network management, as it is clearly prepared for dealing with most existing scenarios. It allows a network analysis at different levels: network modeling, traffic modeling or QoS measurement.

4 Traffic model implementation

4.1 *Introduction*

The current traffic characterization and modeling techniques used in network dimensioning and resource management tasks are still quite inaccurate, mainly due to the difficulty in dealing with the mathematic processes involved, particularly in more realistic and complex queuing systems. Another disadvantage in usual techniques is the need of the *a priori* knowledge of the network traffic matrix.

This chapter will apply a proposed network model by A. Nogueira, P. Salvador and R. Valadas, for predicting network QoS parameters based only on previous measurements (or simulations), not requiring any information either about the network characteristics or traffic matrix. A brief explanation about the model is now presented.

4.2 *Network model concept*

This network model is built from past measurements of two parameters: the traffic that enters and leaves the network at the access points, and the corresponding QoS parameters. The model inference output is the predicted QoS values at those points for different conditions, whether distinct traffic characteristics, users' behavior and number, etc. The model can be applied to any intended QoS parameter, with no restrictions; this metric can be the delay, delay variation, delay bounds, losses, etc, providing much information to the network manager.

The model consists of two blocks: one responsible for modeling the network cross-traffic and another responsible for modeling the network resources and routing. The steps involved in the full process are:

1) The first block receives and transforms the network incoming/outgoing traffic into the users' traffic flow between each pair of network ingress and egress points, where every pair is modelled as a function of all model inputs.
2) The background traffic is added, resulting in the total flow traffic between every pair of network access points.

3) This traffic is transformed by a non-linear function (this function may vary), inserting non-linearity in the model and eliminating the values far from the rest of the data, avoiding the model biasing.
4) The second block receives the transformed total traffic, and models every network QoS parameter as a function of the transformed traffic that flows between each one of the network access points.
5) This block outputs the variable components of the QoS parameters that depend on the traffic throughput.
6) The observed QoS parameters result from the sum of the variable QoS component and the network fixed QoS, which is independent from the network traffic throughput.

This sequence is synthesized in figure 4-1.

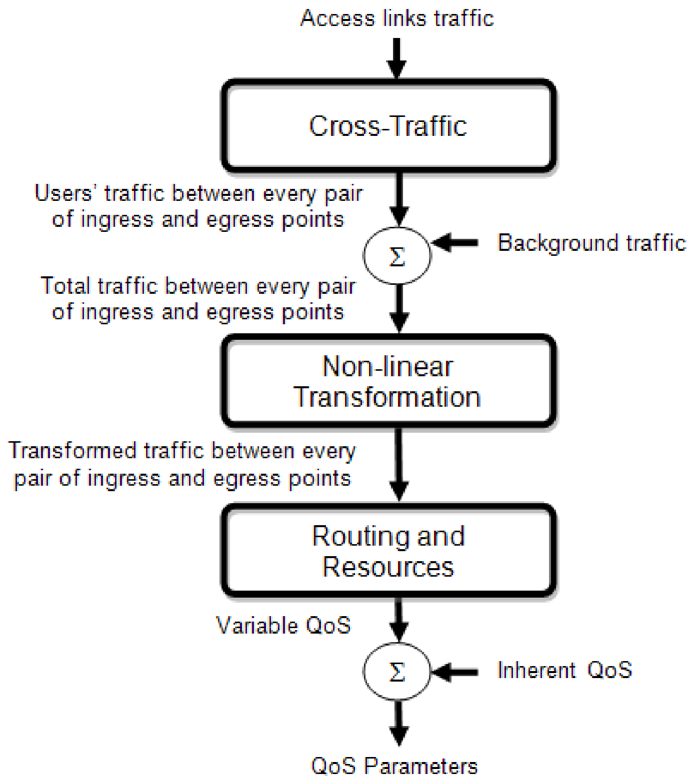


Figure 4-1 – Network model concept

The inference procedure will not be taken into account, as this isn't included on the roll of intended goals. Further work will focus on the practical results derived from the model application on the previously studied Campus scenario.

4.3 *Application of the Model in a Campus Network*

The interest of this experience is to confirm the model efficiency in a situation with the complexity and traffic characteristics of a Campus scale scenario. In order to achieve that, and with the knowledge acquired throughout the previous chapters, one particular scenario simulation was run for furnishing the model with the necessary inputs.

In order to increase results precision, and yet again not greatly increasing the simulation duration, the Campus was considered to be only scenario B used on last chapter. This was done in order to prevent the QoS metrics prediction from being affected by the error associated with the background load at the main link, and because this scenario has enough size to be considered at a Campus scale.

Furthermore, the model was applied to 5 of the departments from this scenario, as the processing complexity varies exponentially with the number of access points considered. This means that the access points measurements included were the incoming and outgoing traffic at the backbone-switch link of these departments. The chosen departments were DECV, IT, DIC, CEMED and ESSUA, because their branch structure simplifies the results collection, and their future appliance in the model. The throughput from the link that connected these departments to the rest of the Campus, from DB to DECV, was also collected, as all ingress and egress access points from the network must be considered. The links of interest are shown in figure 4-2.

The data was filtered using a script, supplying the vectors that would be used as inputs of the model. After this, the model was applied on MATLAB code, using the following inputs:

- Vector with measured traffic in all access points
- Vector with measured QoS metrics
- Type of traffic transformation (linear, sigmoid or tan-sigmoid)
- Number of used values for inferring the model

The type of transformation will be dealt with later in this chapter.

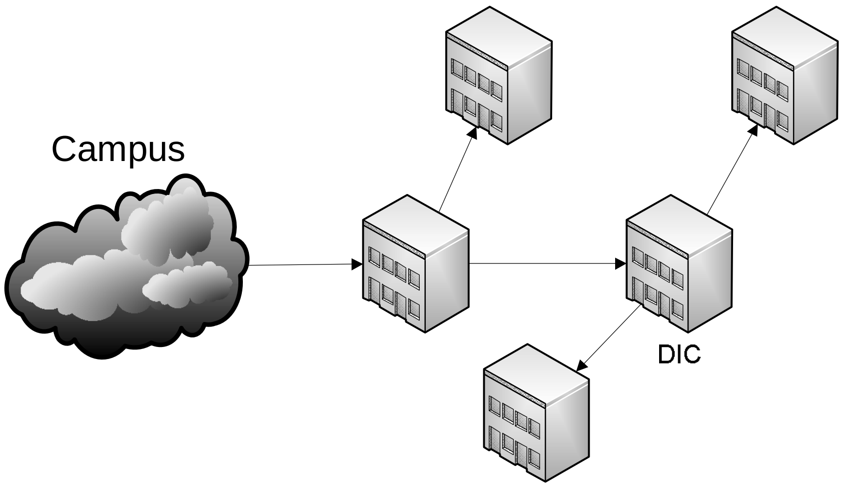


Figure 4-2 – Structure of the network used for model analysis

4.3.1 Users Profile

The used profile is based on Profile 4, with the FTP average packet size increased to 50 MB. The web page size was maintained at 100KB. This allowed a better distinction of the delays between the scenarios simulated, due to the more significant RTT values.

The results for an isolated user were not collected, as these are not relevant for this part, so a description of the studied scenarios will now be brought.

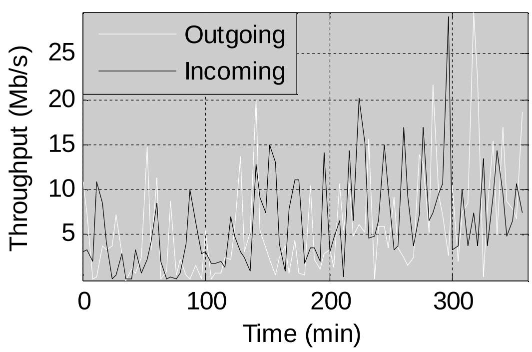
4.3.2 Proposed scenarios

The unpredictability of the network behavior of the Campus scenario will be increased by varying the number of users. The initial simulation was done for 5 users in each department, and the obtained data (initial values of traffic and contemplated QoS parameter) will be used to train the model, that is, for to building the necessary matrices and vectors for the future inference. The QoS parameter used in the model is the average round-trip time (RTT) for each department, measured at the respective access points (AP’s). This statistic was collected at Opnet through the IP ping traffic demand model, as it’s one of its most feasible statistics. The collection of other QoS parameters like end-to-end delay (difference between the time a packet arrives its destination and its time creation) or end-to-end delay variation are packet-derived, where only sent unicast packets are considered, therefore its use in the model wouldn’t be adequate; a possibly profitable use in the model inference would require the results to be weighted according to the traffic exchanged by each user. After training the model, the effective QoS will be predicted by inputting the network throughputs at the access points from the desired scenarios: 10 users per department - Scenario B - and 15 users per department - Scenario C.

It’s important to refer the change of links between all users and switches from 100 Base T to 1000 Base X, due to the fact that the higher transfer peaks by users reached 100Mb/s (results before aggregation) when using the 100 Base T links, which limited the average throughput, handicapping the accuracy of the model results.

For each of the scenarios, the number of collected statistics was 720, and 2 hours were simulated. The results (traffic and RTT) were all aggregated by a level of 24, resulting in a total of 30 statistics in 2 hours, or 1 statistic for each 4 minutes, which can be considered a medium sampling frequency in networks monitoring. The network model was trained using the first 20 values, that is, the first 80 minutes. For a better visualization, the results for the different scenarios are displayed sequentially, where scenario A is represented from initial minute to minute 120, scenario B from minute 120 to minute 240, and scenario C from minute 240 to minute 360. The chosen department to reflect the results was CEMED department (see graphic 4-1), but all other departments’ results can be viewed in Appendix B.3.

The incoming and outgoing traffic for the 3 scenarios at this department is now shown.

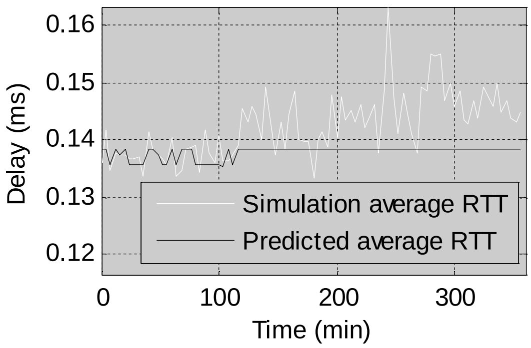


Graphic 4-1 – CEMED department throughput

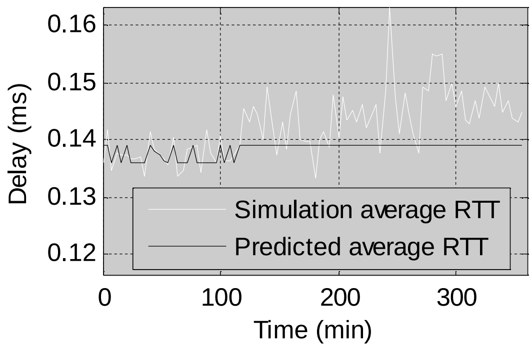
The increase in the traffic when changing from 10 to 15 users per department wasn't much noticeable, but still the peaks are higher for the latter scenario. The model results are presented in the following section.

4.3.3 Results

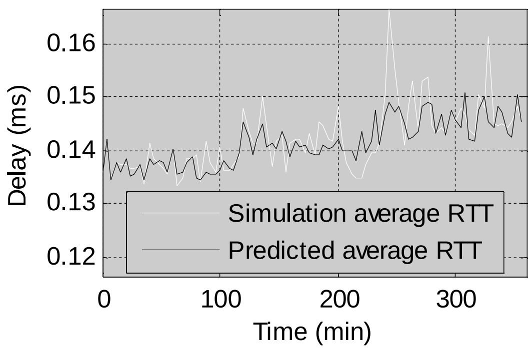
The comparison between the predicted and practical delays is now displayed, and the model accuracy is discussed. The model was tested using 3 different transformations: linear, sigmoid and tan-sigmoid, and its influence in the quality of the outputs is also analyzed. This data is shown from graphic 4-2 to 4-4.



Graphic 4-2 – RTT obtained by simulation and predicted by the inferred network model using sigmoid transformation



Graphic 4-3 - RTT obtained by simulation and predicted by the inferred network model using tan-sigmoid transformation



Graphic 4-4 – RTT obtained by simulation and predicted by the inferred network model using linear transformation

The graphics show that the model was able to predict the RTT behavior for the different scenarios only when using the linear transformation. The other transformations used didn't work out to aid the model prediction, especially with drastic changes in the traffic characteristics, or in the number of users.

The results associated error was obtained using 2 different methods: the first one is the simulation and prediction vectors averages difference, and the second one is the average of the difference between the simulation and predicted vectors. While method 1 points the overall difference between predicted and simulation results, method 2 is more focused on point by point difference, inducing higher errors. The formulas for each method are now shown, where ***di*** is the vector containing the simulation QoS parameters and ***dout*** is vector containing the predicted QoS parameters:

$$\text{Error 1} = \frac{\left|\overline{d_1} - \overline{dout}\right|}{\overline{d_1}}$$

$$Error\ 2 = \overline{\left|\frac{d_1 - dout}{d_1}\right|}$$

The errors were calculated for each department, and according to the scenario; the error on the trained values was also calculated, in order to confirm there were smaller errors on these results. Using linear transformation the predicting error was below 0.61% using method 1 and 2.02% using method 2, representing a very high precision level. This means that at least for an increase in the number of users of 300%, and with a medium sampling frequency the model has valuable and accurate results. As for the rest of the errors, refer to tables 4.1 and 4.2, where the results using both methods are shown.

Department		**CEMED**	**DECV**	**DIC**	**ESSUA**	**IT**
Round-trip-time error 1 (%)	**Training ($\times 10^{-6}$)**	0.04	0.19	0.16	0.02	0.11
	5 users scenario	1.09	0.58	0.45	0.78	0.59
	10 users scenario	0.02	0.16	0.14	0.56	0.47
	15 users scenario	1.41	0.78	1.14	0.35	1.74
	Average	0.61	0.38	0.49	0.02	0.83

Table 1 - Prediction errors for each access point using method 1

Department		CEMED	DECV	DIC	ESSUA	IT
Round-trip time error 2 (%)	Training	0.60	0.47	0.77	0.71	0.63
	5 users scenario	1.52	2.00	1.77	1.68	1.89
	10 users scenario	2.10	2.10	2.18	2.26	2.25
	15 users scenario	2.46	2.20	2.65	2.78	2.64
	Average	1.82	1.76	1.98	2.02	1.98

Table 2 - Prediction errors for each access point using method 2

4.3.4 Conclusion

One of the benefits of the studied model is the potential to obtain precise results in "what if" scenarios without using simulation tools and simply relying on real time measured data, avoiding unnecessary costs (monetary and/or time driven). The versatility of the model also indicates its' possible use in all types of networks, whether LAN's, Wireless Networks or MANET's, as has already been proved by the authors.

Future research needs to be done in order to quantify how solid this method can be, as diverse situations must be studied, particularly scenarios with more distinct behaviors, like scenarios with a larger number of users, using multimedia services like VoIP, overflowed scenarios, etc. More tests should also be done for different sampling frequencies, in order to determine the higher frequency (smaller sampling time) for which the model inference still produces reliable predictions.

Concluding, the model can be allied to network monitoring in a very practical way, and define a new direction in network management.

5 Final Remarks

This dissertation started by presenting important network management concepts, enlightening about the usefulness of simulation and modeling tools in a society that relies on bandwidth for daily work and leisure. Its first part focused on evaluating Opnet as a supporting tool for management tasks, while sharing detailed contents that users will hopefully find helpful when facing the simulator for the first time. While Opnet has an attractive environment for a program in its class, the involved complexity may initially prevent from reaching the expected results, requiring major time investment. The chance to prevent most of the groundwork is of great value; therefore, the presented suggestions should lead the user through the correct path for configuring and simulating the scenarios the expected way. Opnet results' veracity was taken for granted, based on the respect the program has gathered since its creation and previous validations, therefore the interaction between the different entities at the several levels, like users, routers, data links, packets, protocols and queuing methods is assumed to be optimally implemented, in order to produce accurate results.

Overall, Opnet proved to be very adaptable, having multiple possible configurations to provide the intended accuracy to the obtained results. Some minor bugs were found, but most of them can be avoided with some experience with the program. The simulator was tested for Campus scenarios, and was able to produce reliable results on all measured statistics, namely throughput, link utilization, end-to-end delay, ping response time, voice application jitter, and voice application end-to-end delay. Some of these statistics could be used as QoS measurements, giving interesting and relevant information about the network behavior. The program itself revealed useful in management tasks such as studying a network behavior for specific conditions, like the variation in the number of users or in their behavior. It also proved helpful solving previously diagnosed network problems, that require reengineering the network in to reallocate network resources.

As expected, Opnet showed to be appropriate in commercial environments, given its functionalities and optional modules, suggesting being profitable for enterprises and telecom operators, but restricting in other environments, mainly due to its high costs.

The second part of this dissertation was centered on evaluating a modeling framework. The applied network model forecast the network behavior with good accuracy levels for the selected QoS parameter, round-trip time, being one of its major advantages the fact that it does not require any information about the structure of the studied network, like network matrix or topology. In fact, it can be inferred based only on past measurements of traffic on all access points and correspondent QoS parameters, where these parameters can be any of interest to the network manager, like end-to-end delay, end-to-end variation, round-trip time, etc. The great level of information that can be obtained using the model unveils extremely interesting and challenging research topics.

This dissertation has shown that an efficient network monitoring study and management is a key tool for helping a network operator to assure cost-effectiveness in its network planning as well as improve services quality and keep them at proper functioning levels.

Appendix A – Suggestions for Opnet scenarios building

In order to avoid the time spent discovering the optimal way for implementing an accurate scenario, a short list with some key steps to follow is now presented, covering the main configurations and the best way for implementing them.

Find similar projects: Use the tutorial models included in Opnet in order to find out more about the intended network types and protocols.

Type of traffic generated: stations work as simple traffic sources, where it's possible to edit the traffic generation parameters, according to discrete probability distributions (constant, exponential, Poisson, etc), and the routing processes (next hop, destination IP). Workstations generate traffic due to client-server applications, which are defined by the profile and application configurations.

Always verify the links: Opnet enables link verification in a single step (Topology → Verify Links…), detecting most kinds of link failure, like interface unavailability.

Use Rapid Configuration for known topologies: this function allows fast building of topologies like bus, mesh or tree, based on the number of node models and type of links. It's of great use when dealing with a large number of users, and avoids some undetectable errors that occur when placing node by node, link by link.

Avoid editing single nodes or links: when editing large networks, the best option is to select all the devices intended to change and go "edit selected nodes" or "edit similar nodes", for editing all devices of the exactly same type. The same can be applied on links, and avoids monotonous and time wasting tasks.

Use "Copy" and "Paste" in a clever way: if the network to be built is large and has many buildings with identical structures, represent each type of building by a subnet, and simply copy each of the subnets, replicating them the necessary number of times.

Think big: If a network is going to be studied for different amounts of users, the best option is to start building it for the maximum intended number of users, using Rapid Configuration method. For decreasing the number of users, simply delete the excess. This avoids errors that occur when copying users, as sometimes Opnet doesn't refresh all the IP's and other configuration tables by itself. The use of Rapid Configuration with a smaller number of users is a slower option and can affect the network with small differences other than the number of users.

Create a test scenario: it's important to use a small test scenario where all changes can be applied before trying the same in the working scenario. Besides preventing the scenario damage, which sometimes can only be recovered by deleting and replacing devices, these simulations, using 1 or 2 nodes of each required type (example: 1 wireless user accessing a wireless bridge connected to a server) are much faster and conclusions can be retained in few minutes or seconds.

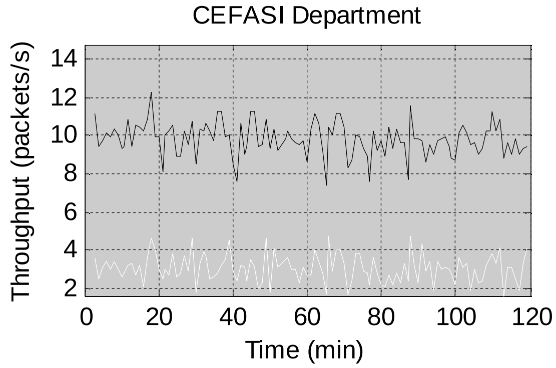
Duplicate the scenario frequently: to avoid problems like the one referred in the previous point, having to replace most of the nodes of links, or even the need to start from the scenario from the scratch, it's advised to save the "good" working scenario, and duplicate it if changes need to be implemented.

Appendix B – Graphical Results

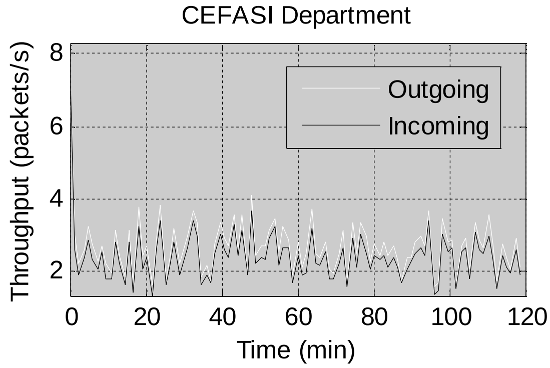
Auxiliary graphical results obtained during the simulations.

B.1 Campus Scenarios

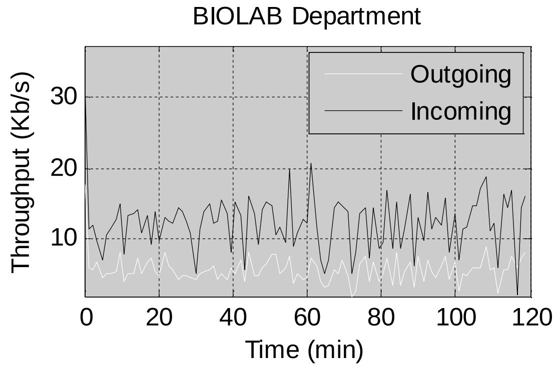
Scenario 1



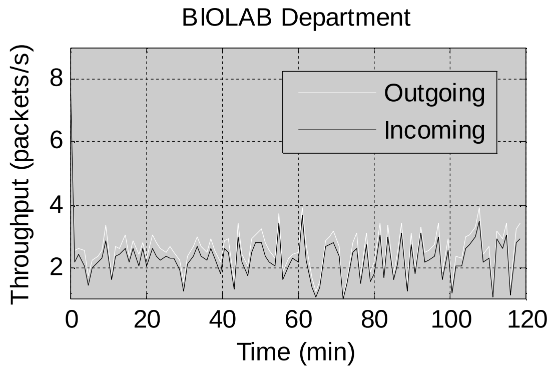
Throughput (packets/s) with unique scenario method



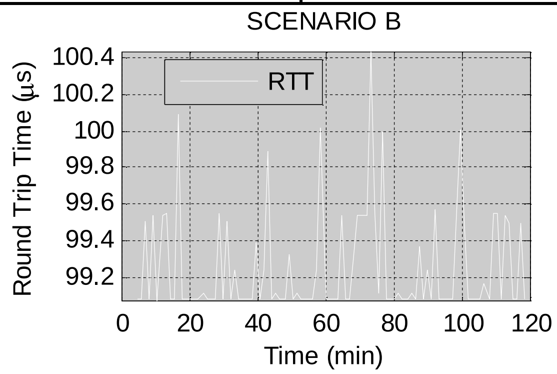
Throughput (packets/s) with split scenarios



Throughput (Kb/s) with split scenarios

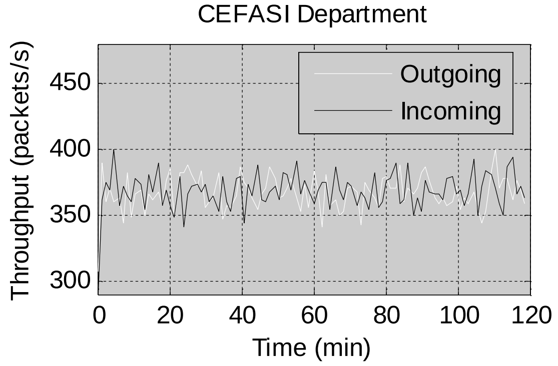


Throughput (packets/s) with split scenarios

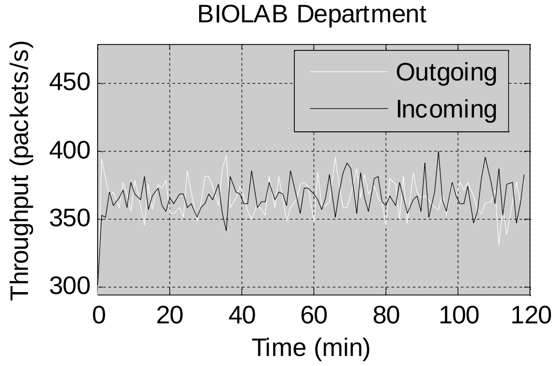


Average round-trip time (µs) with unique scenario for scenario B

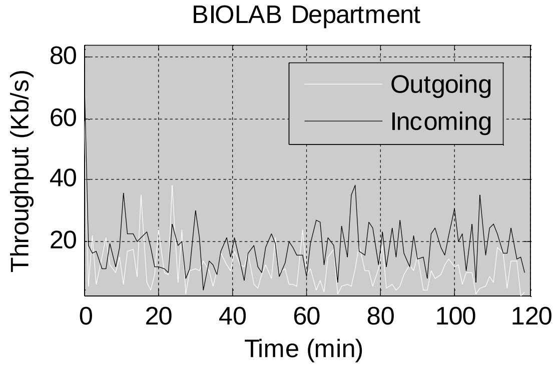
Scenario 2



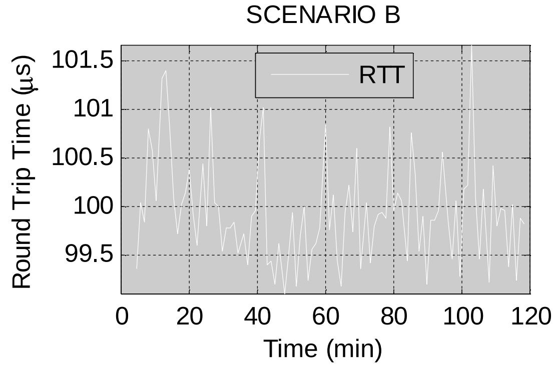
Throughput (packets/s)



Throughput (packets/s)

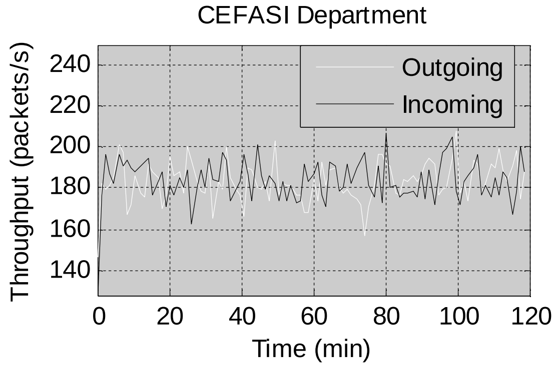


Throughput (kb/s)



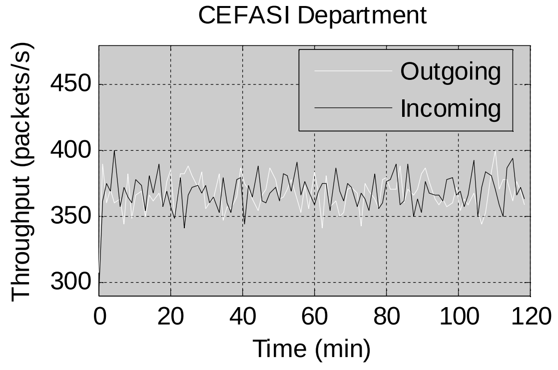
Round-trip time (μs)

Scenario 3 (5 users)

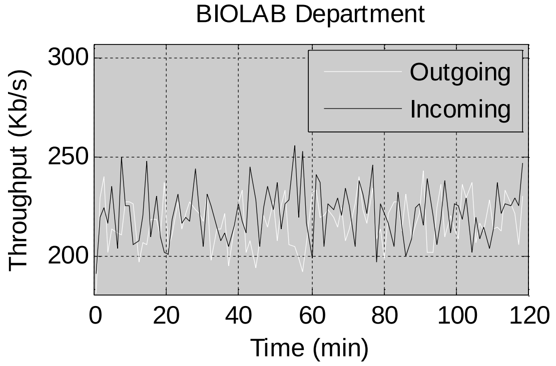


Throughput (packets/s)

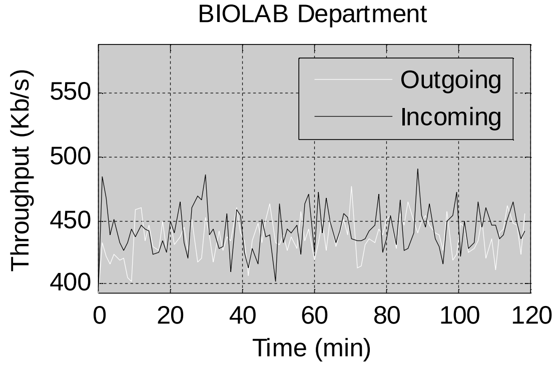
Scenario 3 (10 users)



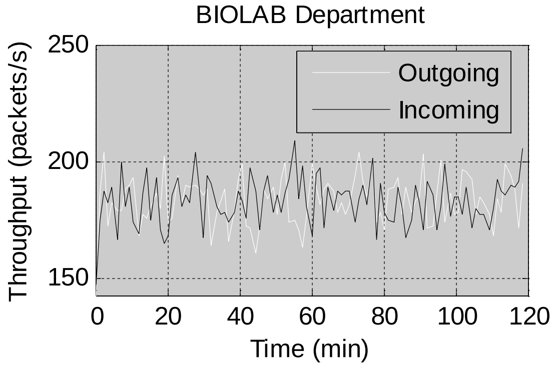
Throughput (packets/s)



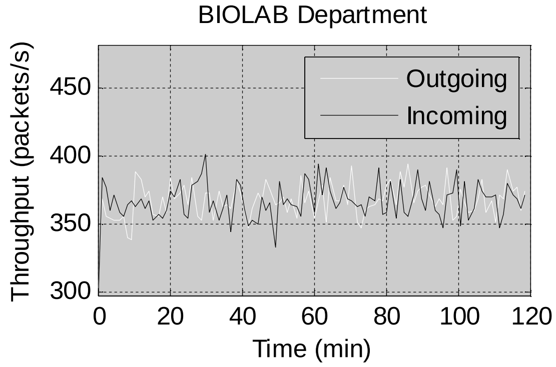
Throughput (kb/s)



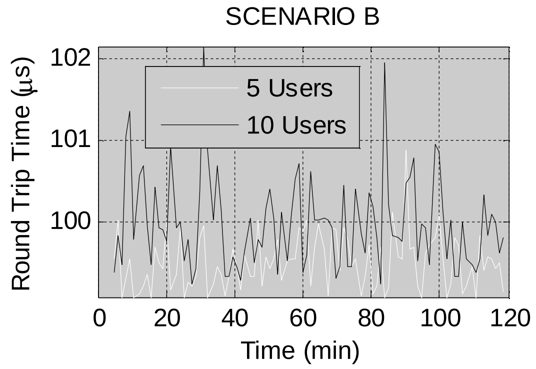
Throughput (kb/s)



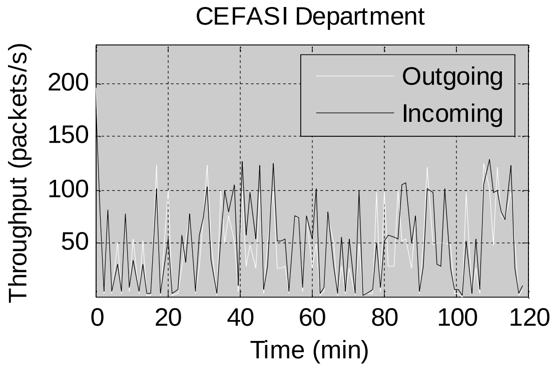
Throughput (packets/s)

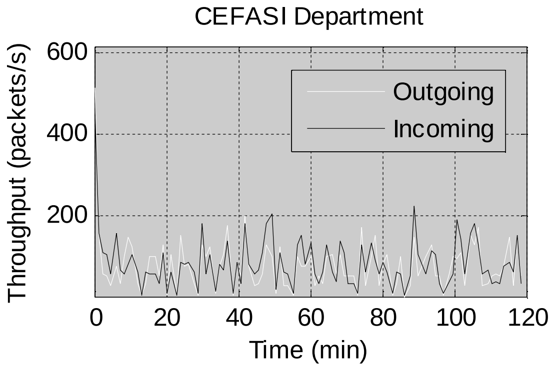


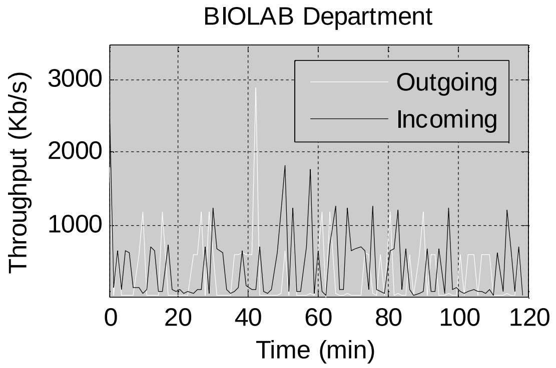
Throughput (packets/s)

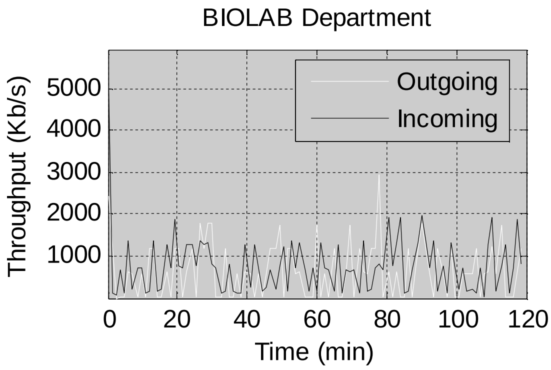


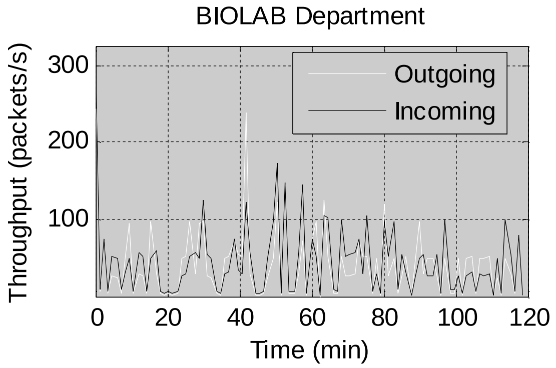
Round-trip time (µs)

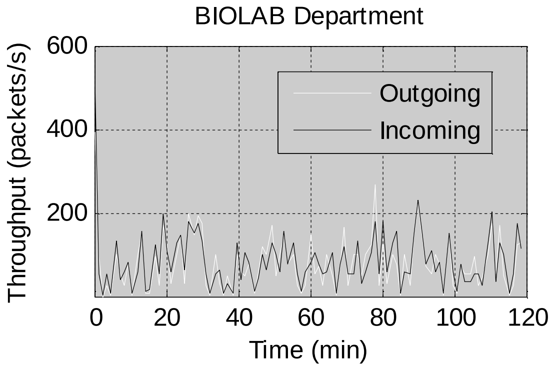
<table>
<tr><th>Scenario 4 (5 users)</th><th>Scenario 4 (10 users)</th></tr>
<tr><td>

Throughput (packets/s)</td><td>

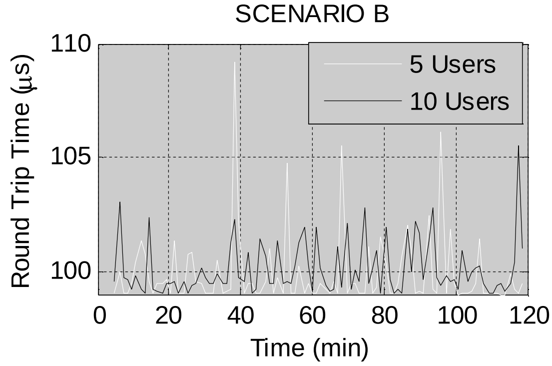
Throughput (packets/s)</td></tr>
<tr><td>

Throughput (kb/s)</td><td>

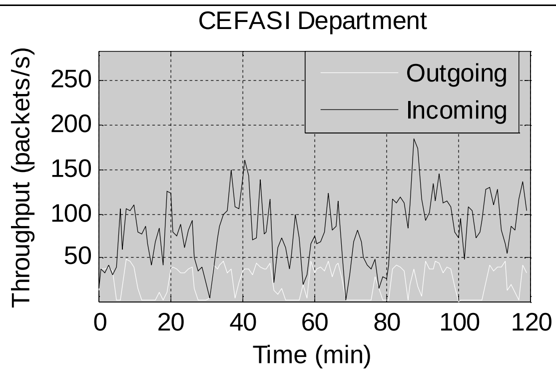
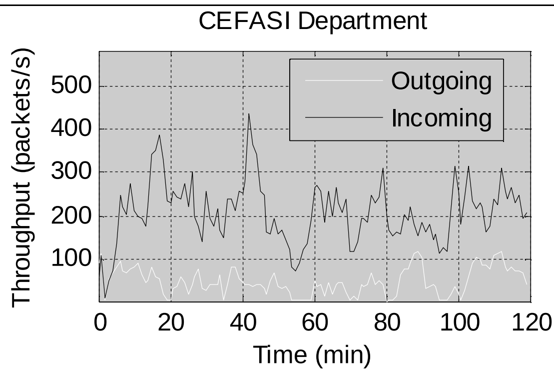
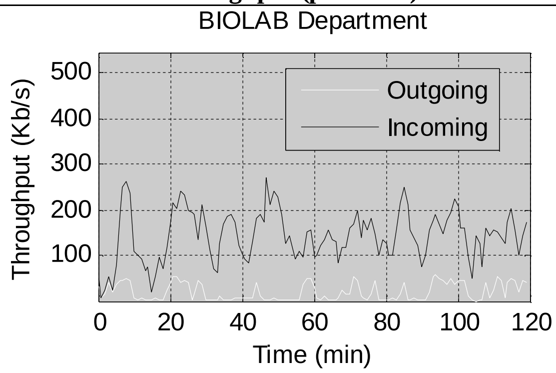
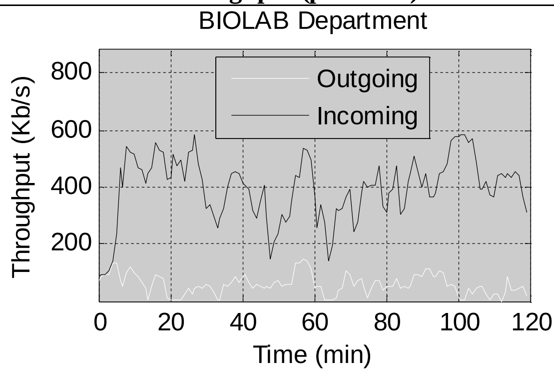
Throughput (kb/s)</td></tr>
<tr><td>

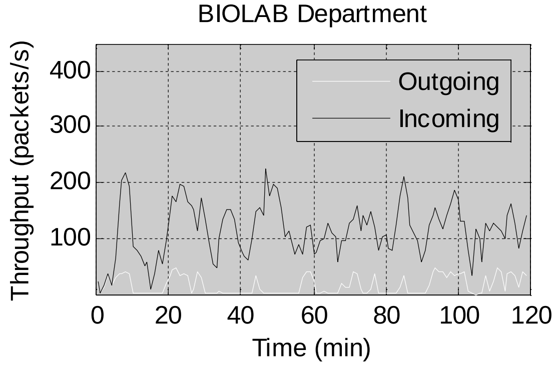
Throughput (packets/s)</td><td>

Throughput (packets/s)</td></tr>
</table>

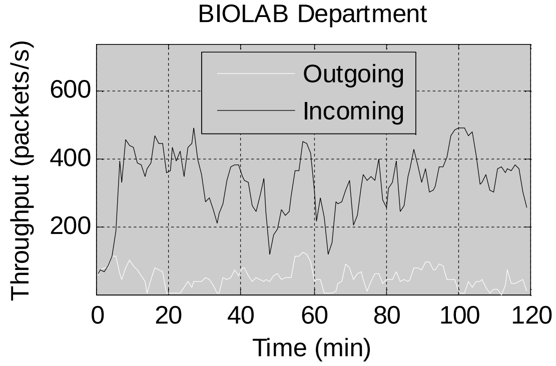


Round-trip time (µs)

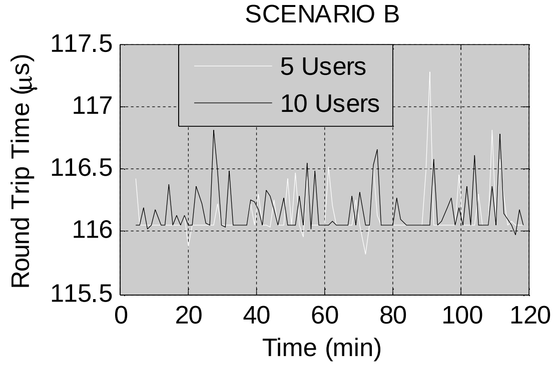
Scenario 5 (1 user / department)	Scenario 5 (3 users / department)
 **Throughput (packets/s)**	 **Throughput (packets/s)**
 **Throughput (kb/s)**	 **Throughput (kb/s)**



Throughput (packets/s)

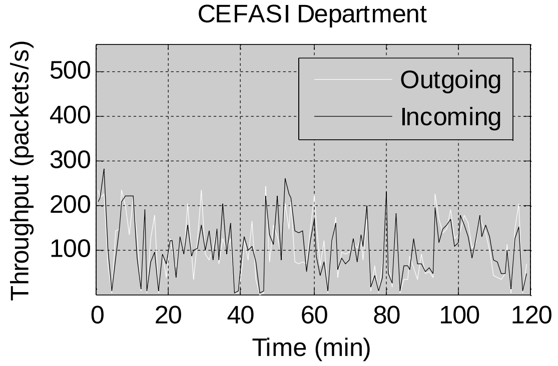


Throughput (packets/s)

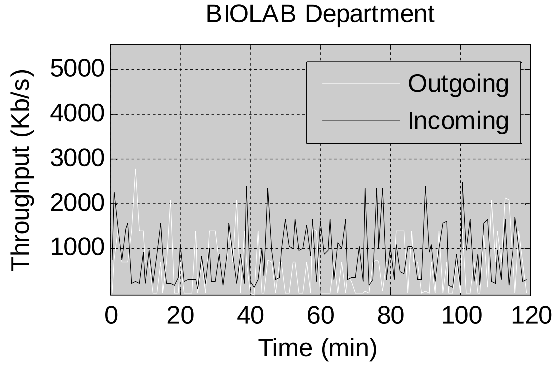


Round-trip time (μs)

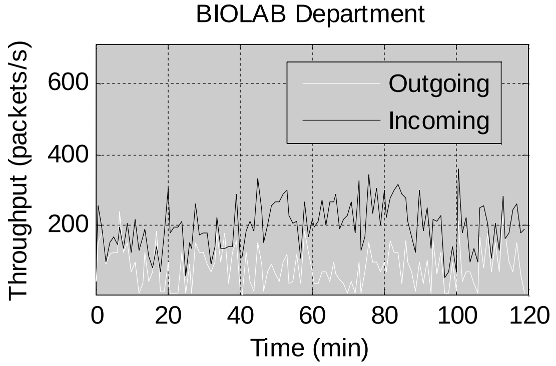
Scenario 6



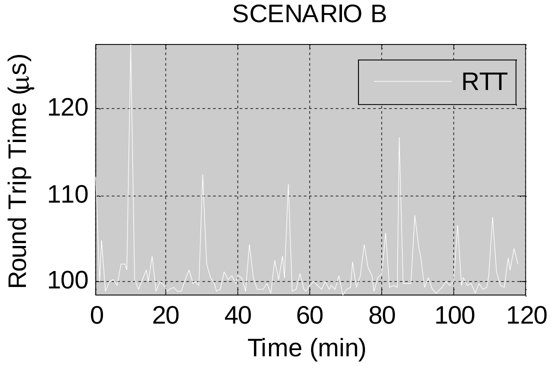
Throughput (packets/s)



Throughput (kb/s)

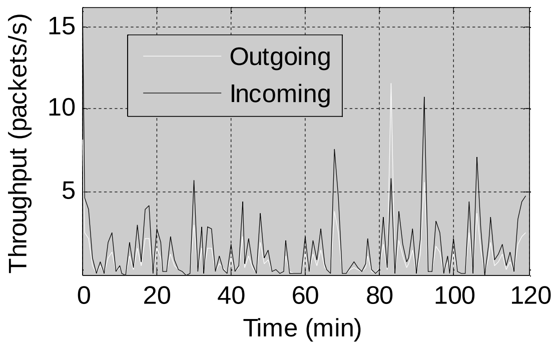


Throughput (packets/s)

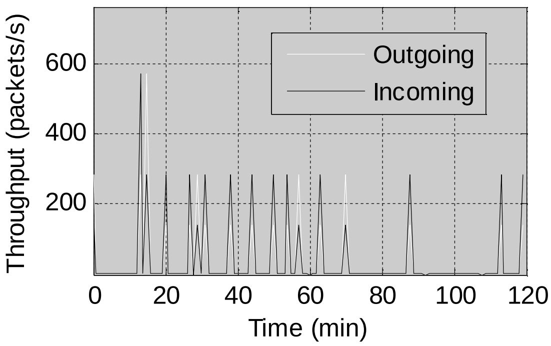


Round-trip time (µs)

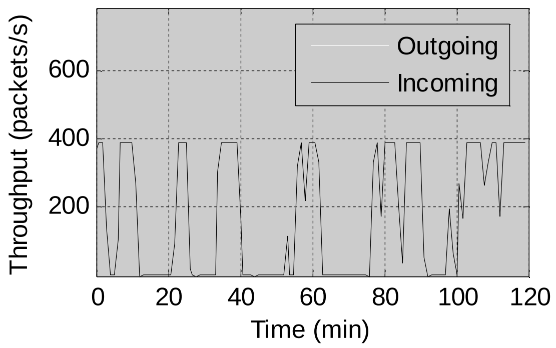
Throughput (packets/s) for QoS profiles



Throughput (packets/s) of Profile A



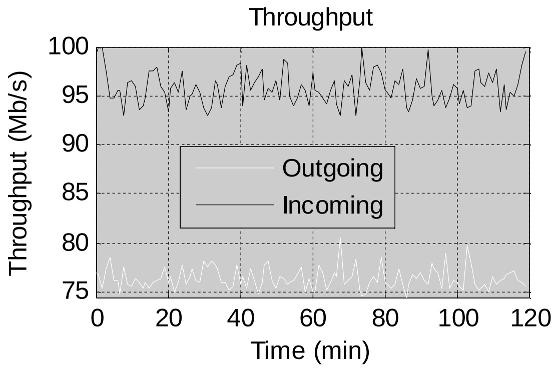
Throughput (packets/s) of Profile B

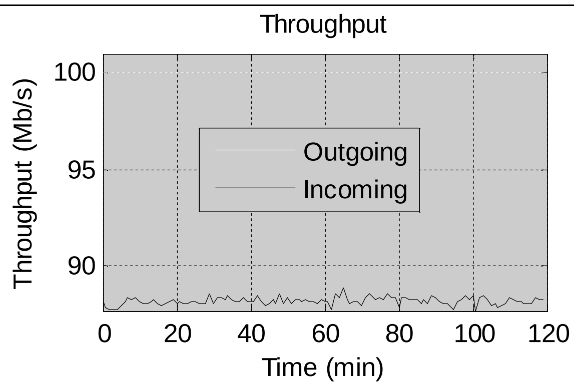


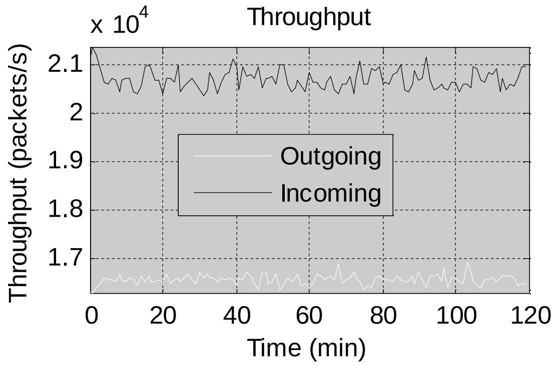
Throughput (packets/s) of Profile C

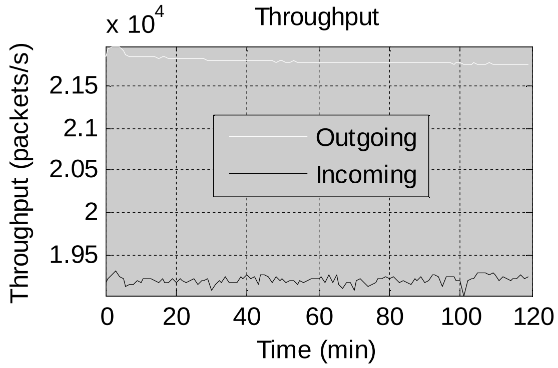
B.2 QoS Scenarios

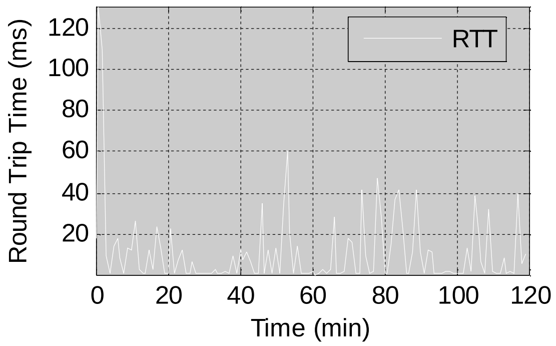
Complementary graphics obtained in the QoS study chapter.

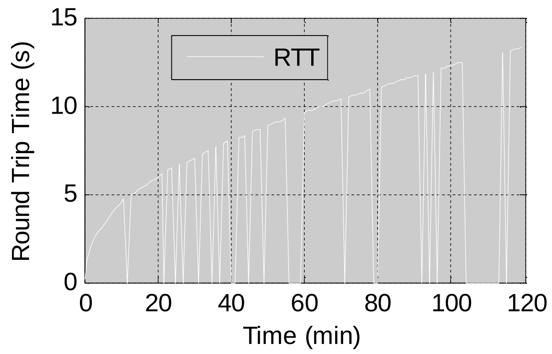
<table>
<tr><th>Case A</th><th>Case B</th></tr>
<tr><td>

Throughput (kb/s)</td><td>

Throughput (kb/s)</td></tr>
<tr><td>

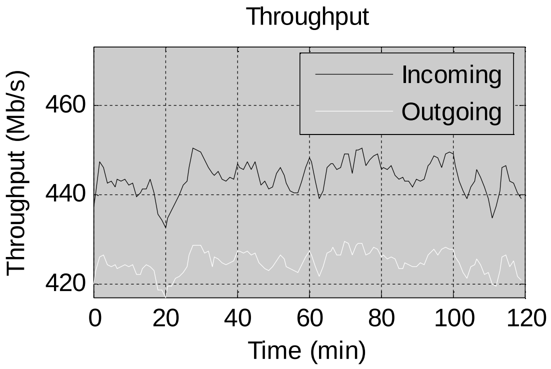
Throughput (packets/s)</td><td>

Throughput (packets/s)</td></tr>
<tr><td>

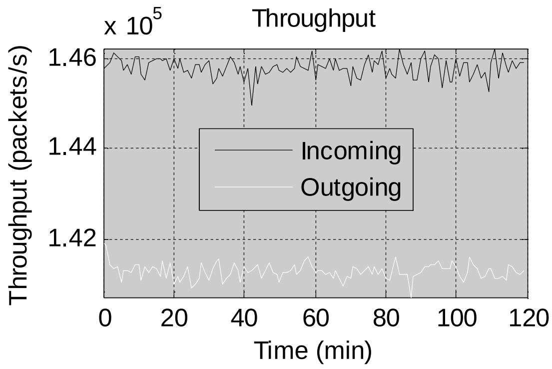
Round-trip time (µs)</td><td>

Round-trip time (µs)</td></tr>
</table>

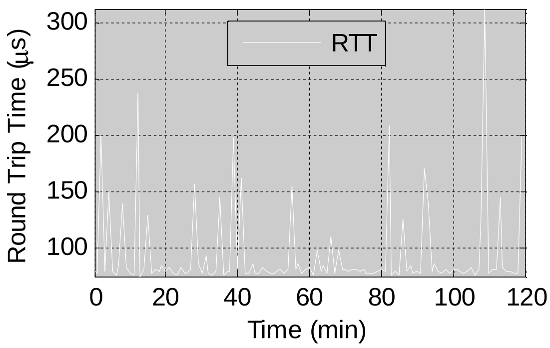
Case C



Throughput (kb/s)



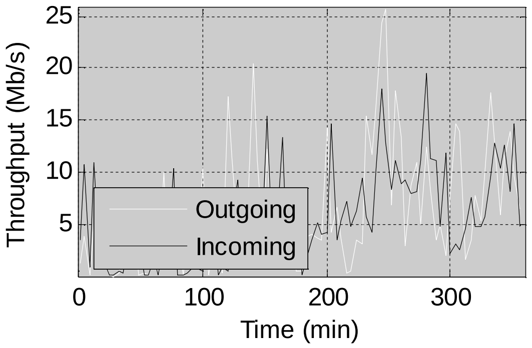
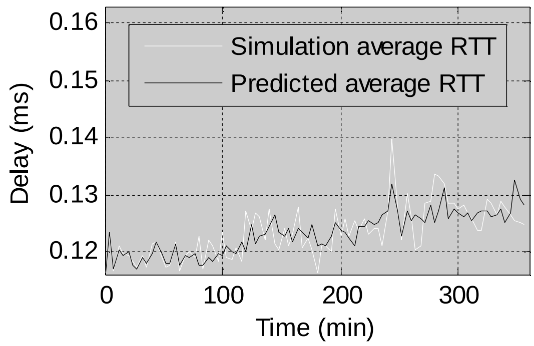
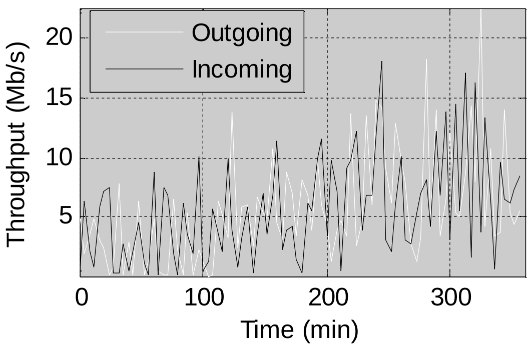
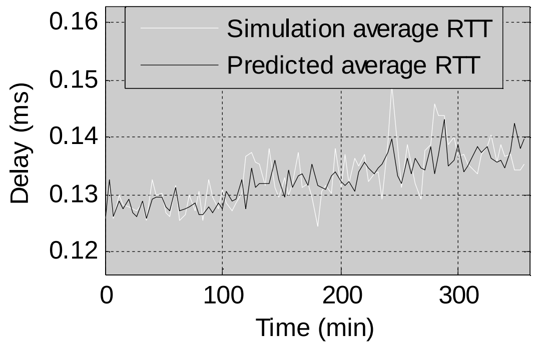
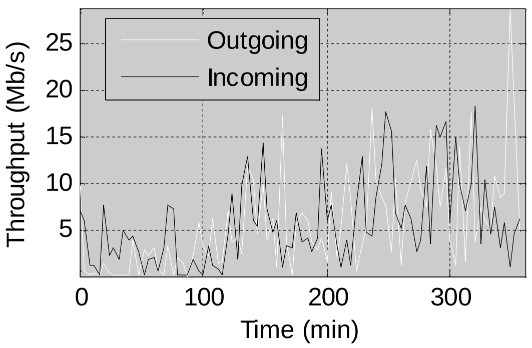
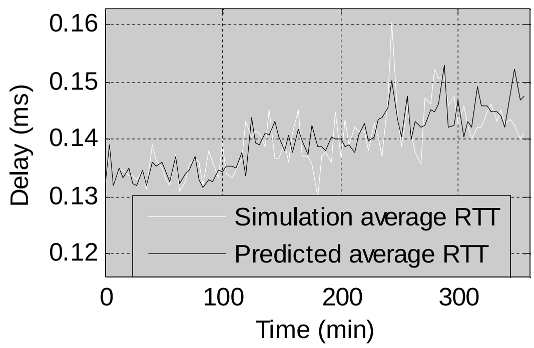
Throughput (packets/s)

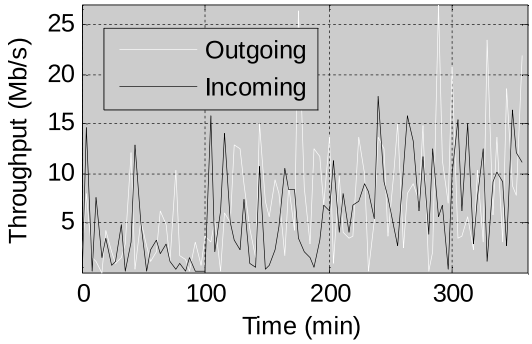


Round-trip time (µs)

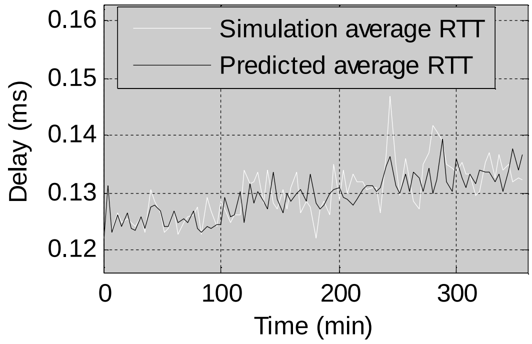
B.3 Model Implementation

The obtained results for the rest of the departments while using the prediction model are displayed here.

Links throughput	Round-trip time
 **DECV department throughput (Mb/s)**	 **DECV RTT (ms)**
 **DIC department throughput (Mb/s)**	 **DIC RTT (ms)**
 **ESSUA department throughput (Mb/s)**	 **ESSUA RTT (ms)**



IT department throughput (Mb/s)



IT RTT (ms)

Bibliography

Books:

[Claise2007] B. Claise and R. Wolter. Network Management: Accounting and Performance Strategies, Cisco Press, 2007.

[Marchese2007] M. Marchese. QoS Over Heterogeneous Networks, John Wiley & Sons, Ltd, 2007.

[Skandier2006] T. Skandier. *Network Administrator Street Smarts – A Real World Guide to CompTIA Network+ Skills*, Wiley Publishing, Inc, 2006.

[Held2003] G. Held. *Ethernet Networks: Design, Implementation, Operation, Management*. John Willey & Sons, Ltd, 2007.

[Anttalainen2006] T. Anttalainen. *Introduction to Telecommunications Network Engineering*, Artech House, 2003.

[Tuomi2007] I. Tuomi. *Networks of Innovation – Change and Meaning in the Age of Internet*, Oxford University Press, 2002.

[Marchese2007] M. Marchese. *QoS Over Heterogeneous Networks*. John Wiley & Sons, Ltd, 2007.

[Banks2005] J. Banks, J. Carson, B. Nelson and D. Nicol. *Discrete-event system simulation - fourth edition*, Pearson, 2000.

[Law2000] A. M. Law, W. D. Kelton. *Simulation modeling and analysis - third edition*, McGraw-Hill, 2000.

[Zeigler2000] B. P. Zeigler, H. Praehofer and T. G. Kim. *Theory of modeling and simulation: Integrating discrete event and continuous complex dynamic systems - second edition*. Academic Press, 2000.

[O'Driscoll2008] Gerrard O'Driscoll, *Next Generation IPTV Services and Technologies,* John Willey and Sons, Inc, 2008.

Articles and Documents:

[Salvador2007] P. Salvador, A. Nogueira and R. Valadas. "Predicting QoS Characterístics on Wireless Networks", 2007.

[Salvador2007] P. Salvador, A. Nogueira and R. Valadas. ”Local Area Network Modeling for Performance Prediction”, 2007.

[Nogueira2007] A. Nogueira, P. Salvador and R. Valadas. "Joint Modeling of MANET Characteristics for QoS Prediction", 2007.

[Trivedi] K. S. Trivedi. "Discrete Event Simulation: Tools and Applications".

[Fahmy1996] H. I. Fahny, C. Douligeris. "Automatic Network Modeling, Simulation and Performance Evaluation", 1996.

[Nogueira2003] A. Nogueira, P. Salvador, R. Valadas. "Modeling Network Traffic with Multifractal Behavior", 2003.

[Park2003] T. Park, A. Dadek. "OPNET Simulation Modeling and Analysis of Enhanced Mobile IP", 2003.

[Mohorko2007] J. Mohorko, M. Fras, Z. Cucej. "Modeling Methods in OPNET simulations of Tactical Command and Control Information Systems", 2007.

[Wunnava2001] S. V. Wunnava, G. V. Crosby, A. Kapasi. "Adaptive Network Modeling Scheme", 2001.

[Schilling2005] B. Shilling. "Qualitative Comparison of Network Simulation Tools", 2005.

[Zubairi2000] J. A. Zubairi, M. Zuber. "Suny Fredonia Campus Network Simulation and Performance Analysis using Opnet", 2000.

[Lucio2003] G. F. Lucio, M. Paredes-Farrera, E. Jammeh, M. Fleury, M. J. Reed. "Opnet Modeler and Ns-2: Comparing the Accuracy of Network Simulators for Packet-Level Analysis using a Network Testbed", 2003.

[Kishore] M. Kishore. "Optimal Link Utilization and Enhanced Quality of Service Using Dynamic Bandwidth Reservation for Pre-recorded Video", 2003.

[Papagiannaki] P. Papagiannaki, R. Cruz, C. Diot. "Network Performance Monitoring at Small Time Scales".

[Alberti] M. Alberti, R.S. dos Santos, T. F. Lopes, H. F. A. Alves, C. F. C. Vallvé. "Ensinando Qualidade de Serviço na Internet com o Opnet Modeler".

[Santos] R. S. Dos Santos, H. F. A. Alves, T. F. Lopes, C. F. Casanova, A. M. Alberti. "Análise da Qualidade de Serviço (QoS) para Serviços Multimídia na Internet".

Links:

“Opnet Technologies”, http://www.opnet.com/, (accessed on 10/2007)

“A Collection of Modeling and Simulation Resources on the Internet”, http://www.idsia.ch/~andrea/simtools.html#network, (accessed on 01/2008)

“The New York Times - Technology”, http://www.nytimes.com/pages/technology/index.html, (accessed on 06/2008)

“Web Site Optimization”, http://www.websiteoptimization.com/, (accessed on 03/2008)